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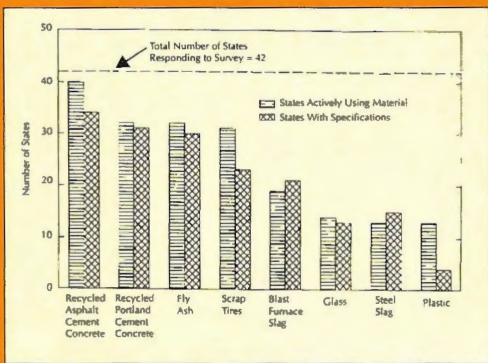
Waste & Recycled Materials in Highway Construction



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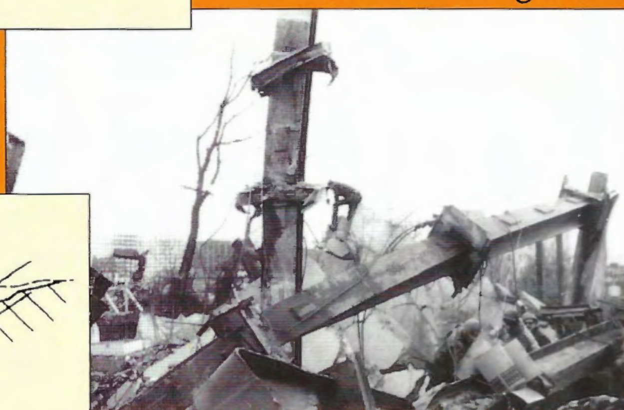

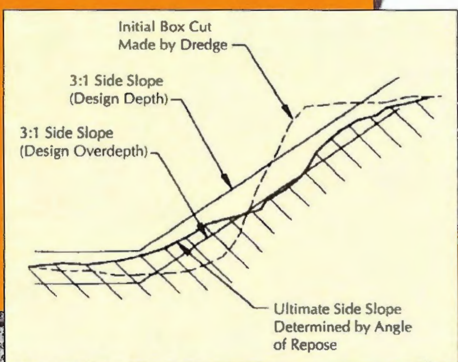

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CONTENTS

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Addendum

Charles B. Scott and Steve Johnis, authors of the paper "An Innovative Bulk Barge Fender System" published in the Fall/Winter 1997 issue of *Civil Engineering Practice* (pp. 49-64) were recipients of BSCES's 4th Annual Ernest A. Herzog Award on November 16, 1995.

The Use of Waste & Recycled Materials in Highway Construction

Currently, while there is significant use of waste and recycled materials, each application must be thoroughly investigated to determine the optimal beneficial use and any negative impacts.

WAYNE M. SHELBURNE & DON J. DEGROOT

The amount of municipal solid waste generated in the Commonwealth of Massachusetts continues to grow and is a major concern for the state. In the 1994 Massachusetts Solid Waste Master Plan, the Massachusetts Executive Office of Environmental Affairs and Massachusetts Department of Environmental Protection (DEP) reaffirmed the goal of recycling and composting 46 percent of municipal solid waste generated within the commonwealth by the year 2000. Emphasis is being given to recycling because:

- It conserves natural resources and energy;
- It helps protect water and air quality by reducing the amount of waste that is landfilled or burned; and,
- It helps drive economic development by stimulating manufacturing industries capable of using the recyclable materials as raw material.

A necessary component of achieving that recycling goal is to develop sustainable markets for waste and recycled materials that are diverted from traditional disposal methods such as landfilling. The transportation industry has been identified as such a market. While transportation agencies — such as the Massachusetts Highway Department (MHD) — have been using waste and recycled materials (WRMs) in highway construction, many believe that there is significant potential for much greater use. However, since WRMs are not common construction materials, there are concerns about their suitability and practicability for use in transportation applications. Specific issues of concern include physical and chemical properties, constructability, quality control, field performance, long-term physical and chemical stability, and environmental impact.

Classification of Waste & Recycled Materials

The United States generates approximately

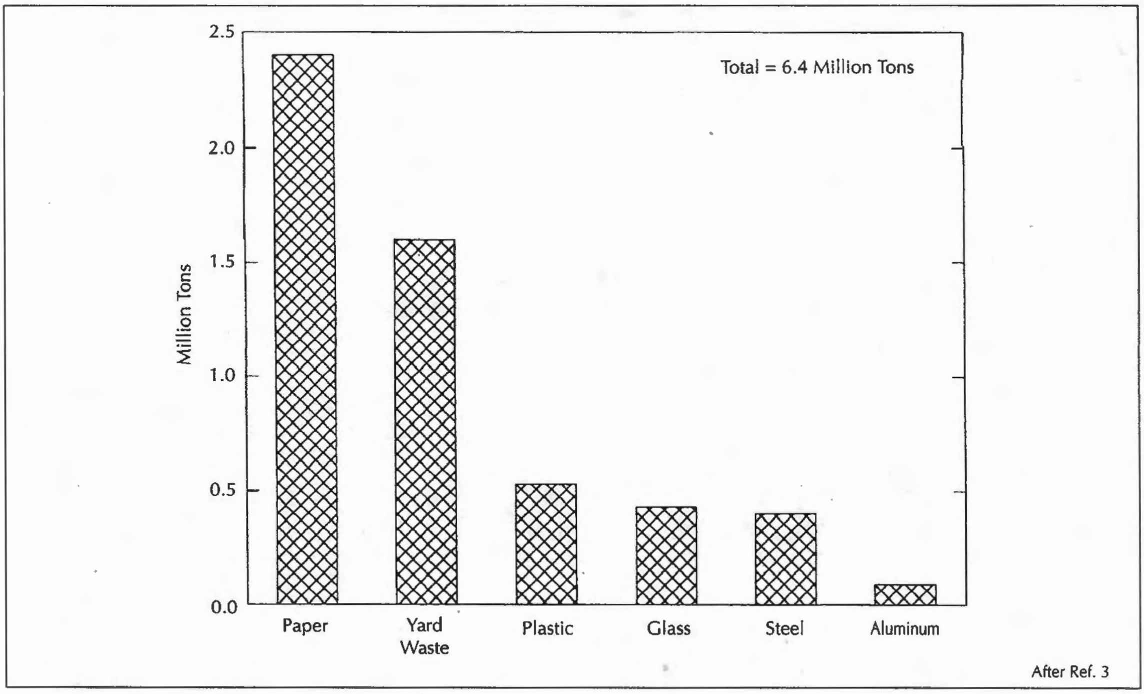

FIGURE 1. Estimated 1992 distribution of municipal solid waste in Massachusetts by weight.

4,500 million tons of waste per year. This waste can be classified into four major groups based on their generation source:[1]

- Domestic (200 million tons);
- Industrial (400 million tons);
- Mineral (1,800 million tons); and,
- Agricultural (2,100 million tons).

Domestic Waste. Domestic waste is composed mostly of household and commercial trash, of which approximately 62 percent is landfilled, 22 percent is recycled and 16 percent is burned.[2] Many components of domestic waste can be recovered and used in manufacturing new products — with paper, glass and plastics being the most common. Leaf and yard waste make up a significant portion of the waste stream, yet its disposal in landfills has been banned in many states in an effort to encourage the processing of this waste material into compost. In many locations, wastewater sludge (or biosolid waste) is also diverted from landfills for processing into compost.

Other sources of domestic waste — such as scrap tires — are more problematic. Approximately 235 million tires are discarded annually, of which approximately 80 percent are landfilled and 10 percent are burned for fuel. However, in 22 states tires are not allowed in landfills, which has led to the stockpiling of approximately 2 to 3 billion tons of scrap tires across the country. Stockpiled scrap tires pose health and environmental hazards, since they are breeding grounds for mosquitoes and various rodents and can often burn uncontrollably.[1]

In 1992, Massachusetts generated a total of 6.4 million tons of municipal solid waste (see Figure 1), of which 47 percent was combusted, 28 percent was composted or recycled, 19 percent was landfilled and 6 percent was exported. As of 1992, Massachusetts had 122 active landfills and nine operating combustion facilities that processed 3 million tons of municipal solid waste.[3] Massachusetts also generates approximately 6 million scrap tires per year, with 5 to 10 million scrap tires already stockpiled as of 1993.[4]

Industrial Waste. Various industrial processes — such as the production of metals and coal and the burning of coal for energy — produce large amounts of waste. Some of the more common waste types are coal combustion by-products, blast furnace slag from iron production, steel slag, recycled asphalt and concrete, foundry wastes and roofing shingle waste. Approximately 100 million tons of recycled paving materials and 70 million tons of coal ash are generated each year, with approximately 50 percent and 25 percent, respectively, of these materials being reused.[1] Blast furnace slag and steel slag are typically recovered and sold in areas where iron and steel are produced. Waste foundry sand consists of natural sand that is used as molds for metallic castings, while roofing shingle waste consists of scrap material left over from the production of shingles and from construction and demolition.

Mineral Wastes. Mineral wastes are produced from mining processes, including waste rock from surface mining operations, mill tailings from ore concentration processes, quarry waste from stone washing and screening at quarries, and coal refuse from the cleaning of coal. The largest fraction of these wastes is waste rock, with approximately 1,000 million tons generated per year.[1] Mineral wastes are usually used as stone fill for embankments, riprap and subbase. However, their use is generally limited to the area of their production because of prohibitive transportation costs to ship them elsewhere.

Agricultural Waste. Crop wastes, animal manure, lumber and wood wastes, and other organic wastes make up the largest fraction of this waste stream. Of these wastes, the largest component generated is animal manure (at approximately 1,600 million tons per year).[1] Although agricultural wastes have limited application in highway construction, animal manure and crop wastes can be used as a soil amendment (*i.e.,* compost) for roadsides. Wood waste can be used for mulch and has been used experimentally as lightweight embankment fill. As is the case for mineral wastes, transportation costs are the major barrier to increased use of these waste materials.

Recycling Waste Materials

Recycling is one of the primary ways of reducing the volume of waste that needs to be disposed. It has been strongly encouraged by federal, state and local governments because it is believed to conserve natural resources and help protect the environment through reduced landfilling and incineration of waste. While there is some controversy regarding the cost effectiveness of these benefits,[5,6] it is clear that landfill area is becoming scarce. During the coming decade, many landfills will be closed due to a lack of the proper liner systems that are required by recently promulgated federal and state regulations; and it has become increasingly difficult to site new landfills. These problems have created the need for a plan to reduce the amount of material landfilled per year.

For example, the 1994 Massachusetts Solid Waste Master Plan called for the recycling and composting of solid waste to reach 46 percent, combustion to increase to no more than 50 percent, and landfilling to diminish from 42 percent to 4 percent by the year 2000.[3] These types of waste disposal goals are being met with help from legislative acts requiring recycling and the use of recycled materials, technical and financial assistance for recycling, and voluntary incentives for businesses to use recycled products. Out of the 351 municipalities in Massachusetts, 341 have a recycling program,[3] including 251 communities that compost their leaves.[7] While significant achievements have been made to reach federal and state recycling goals, attaining the future goals will require a greater effort, including the development and expansion of markets such as highway construction using waste materials.

Federal & Massachusetts Regulations

As indicated above, state and federal regulations have played a key role in the recycling of waste materials and their potential use in highway construction. Although there has been a general increase in recent years in public awareness and concern over the impact of waste disposal on the environment, most waste reduction and recycling programs in the private and public sectors historically have been reactive rather than proactive — that is, individuals and businesses are often recycling waste materials because federal and state regulations require or strongly encourage them to do so. At the federal level, the 1976 Resource Conservation and Recovery Act and the 1984 Hazardous and Solid Waste Amendments pro-

TABLE 1.
Current & Potential Uses for Waste & Recycled Materials in Highway Construction

Waste & Recycled Material	Current & Potential Applications
Recycled Asphalt Cement Concrete	Asphalt cement concrete aggregate; Portland cement concrete aggregate; aggregate for base and subbase; embankment fill
Recycled Portland Cement Concrete	Asphalt cement concrete aggregate; Portland cement concrete aggregate; aggregate for base and subbase; embankment fill; rip-rap
Coal Combustion Fly Ash	Asphalt cement concrete; Portland cement concrete; roller compacted concrete; flowable fill; road base stabilization, embankment fill
Coal Combustion Bottom Ash	Aggregate for base and subbase; lightweight Portland cement concrete aggregate; sandblasting; embankment fill; deicer
Scrap Tires (Crumb Rubber)	Asphalt cement binder; crack sealant; stress absorbing membrane interlayer; railroad crossing mats; Portland cement concrete aggregate
Scrap Tires (Shredded)	Base course insulator; embankment fill; retaining wall backfill; blasting mats; noise walls; retaining wall blocks
Plastics	Asphalt cement concrete aggregate; Portland cement concrete aggregate; drain pipes; delineator posts; cones; fences; barrels; noise walls; miscellaneous construction items; guardrail offset blocks; speed bumps; sign blanks; car stops; plastic lumber; geotextiles
Glass	Asphalt cement concrete aggregate; Portland cement concrete aggregate; base course aggregate; drainage aggregate; embankment fill; traffic paint
Compost	Topsoil upgrading; turf establishment; landscaping; weed control; erosion control; siltation control
Blast Furnace Slag	Asphalt cement concrete aggregate; Portland cement concrete aggregate; base course aggregate; deicer; embankment fill
Steel Slag	Asphalt cement concrete aggregate; Portland cement concrete aggregate; base course aggregate; friction aggregate; blasting grit; embankment fill
Foundry Sand	Asphalt cement concrete aggregate; Portland cement concrete aggregate; flowable fill; deicer; embankment fill
Shingles	Asphalt cement concrete; cold patch

moted waste reduction through reuse and recycling. The 1991 Intermodal Surface Transportation Efficiency Act (ISTEA) originally required specific quantities of crumb rubber in asphalt but has since been rescinded in the face of significant opposition from state departments of transportation (DOTs). The federal Environmental Protection Agency's (EPA) *Comprehensive Guideline for Procurement of Products Containing Recovered Materials* presents specific guidelines for the purchase and/or reuse of many materials that can be used in highway construction — such as fly ash, blast furnace slag, plastic products and compost. These guidelines must be used by federal procuring agencies and those governing bodies that receive federal funds when spending more than ten thousand dollars per year on a single item. In Massachusetts, the most significant legislative item is Section 71 of the 1994 Transportation Bond Bill that specifically requires the MHD to report to the governor and the legislature on its past, current and future use of waste and recycled materials.

Applications for Waste & Recycled Materials in Highway Construction

Table 1 summarizes some of the many current and potential applications for WRMs in highway construction. While some of these applications have long been common practice, others are still considered experimental. In fact, in some cases, it may eventually be shown that some of these applications are inappropriate.

Recycled Asphalt Cement Concrete. Recycled asphalt cement concrete or pavement (RAP) consists of old asphalt road surfaces that are milled away prior to repaving operations. Significant quantities of RAP are produced each year, and its reuse in highway construction has been common for many years. It is typically recycled into new asphalt pavement (hot in-place recycling) or grinded into a homogeneous mix and used in place as a base course (cold in-place recycling). When reused as an aggregate for new asphalt cement concrete, typical percentages used range from 15 to 50 percent (by weight). In addition to these quantity limits, the quality of the RAP source is very important (*i.e.*, whether from better quality mix design interstate highway versus lower quality mix design secondary roads). Typically, RAP is tested for such properties as gradation, asphalt content and viscosity, and, in some cases, additives may be used to bring the RAP to within specifications.

Recycled Portland Cement Concrete. Recycled Portland cement concrete (RPCC) from pavement and demolition debris is often used in highway construction for several applications. RPCC that has been removed from sites and processed (to remove reinforcing steel and to break it down into a suitable gradation) can be used as an aggregate source for Portland cement concrete, asphalt cement concrete, base and subbase (up to 100 percent) in new road construction, embankment fill and rip-rap. It is not recommended for use in Portland cement concrete that will be used in structural applications (for example, bridge decks, abutments, etc.) because of concerns about the presence of deleterious materials and reduced compressive strength.[8]

For other applications, the processed aggregate typically must meet the same specifications (for example, gradation, Los Angeles abrasion, etc.) as natural aggregates for the intended use. In some of the more densely populated regions of the country, RPCC is the major source of base course material because of depleted sources of natural aggregates and high hauling costs. For example, in the New York metropolitan area, nearly all material placed as subbase for state highways consists of RPCC.[9] Existing Portland cement concrete roads can also be fractured or crushed in place and compacted to serve as a base material for new asphalt cement concrete. This practice provides a particular benefit because it reduces construction costs for the removal and transportation of the waste concrete.

Coal Combustion Fly Ash. Fly ash is the finer-grained waste material that is recovered from flue gases during coal combustion. It is a pozzolon; therefore, when mixed with calcium and water, it will develop cementitious compounds. As a result, fly ash has long been used as a beneficial additive to Portland cement concrete as a substitute for Portland cement (typically 15 to 30 percent by weight). In fact, the American Society for Testing and Materials (ASTM) has developed standards for the use of fly ash in concrete. Fly ash is also a common ingredient in controlled density fill (*i.e.*, flowable fill) in quantities ranging from approximately 10 to 100 percent (by weight) and is also used in roller-compacted concrete and for soil stabilization.

Scrap Tires. The use of scrap tires in highway construction is one of the most controversial uses of waste and recycled materials. Ground-up scrap tires with the steel belt removed (known as crumb rubber) can be used as an aggregate in new asphalt (dry method) or, when heated, as a binder in new asphalt (wet method). It has been used successfully for over fifteen years in certain parts of the country (for example, in Arizona) and is reported to result in longer pavement life due to decreased thermal cracking, potholing, deformation and reflective cracking. It can also result in reduced driving noise due to the resilient nature of the rubberized asphalt.

However, critics of the use of crumb rubber in asphalt claim that its use involves a substantial increase in cost over conventional pavement mixes and can cause unacceptable air emissions during mixing and placement. ISTEA stipulated minimum percentages of asphalt containing recycled rubber that can be used on all federally funded highway construction. States that failed to satisfy these minimum requirements would have had a percentage of their federal highway apportionments with-held. Many state DOTs strongly opposed these requirements due to technical and economic concerns, and, as a result, Congress repealed this provision in the 1995 National Highway System Act. Some states have been successfully experimenting with lower rubber content and smaller rubber particles in crumb rubber modified asphalt than that originally mandated in ISTEA. For example, the Florida DOT has been using only 12 percent rubber (maximum nominal 40-mesh) by weight of asphalt cement in its open-graded surface mixtures and 5 percent (maximum nominal 80-mesh) in its dense-graded mixtures. While the initial cost for using the rubber asphalt is higher, Florida DOT feels that this increase is offset by improved performance of the highway and the salvaging of tons of waste tires from landfills.[10]

Shredded tires (without the belt removed) have been used as backfill material for roads, embankments and retaining walls. The scrap tires act as a lightweight, easy-draining backfill material and provide an insulating layer against frost penetration when used as a base or subbase aggregate.[11,12] These applications offer the potential to use significant quantities of scrap tires since, in some cases, up to 100 percent of the fill is made of scrap tires.

Concerns have been raised over the potential for the leaching of contaminants from the tires to ground water. Therefore, some practitioners recommend using scrap tires only in the unsaturated zone. A more recent problem has risen in Washington state where two embankment fills made of scrap tires caught fire. The problem required the excavation and removal of the tire fill under difficult conditions and at considerable expense. It is still uncertain what the causes of the fires were, but one theory was that exothermic reactions may have been producing heat, which led to the oxidation of the steel belts and to microbial action on tire rubber.[13]

Scrap tires are one of the country's major waste disposal problems, and many have looked to the highway construction industry as a strong market for their reuse. While, in some cases, their use has proved to be successful, it is also apparent that there are still problems. Many organizations and universities are actively conducting research on the use of scrap tires, and it is likely that within the next decade the most appropriate uses of scrap tires in highway construction will be identified.

Plastic. Recycled plastic has many applications for highway construction, especially for non-structural items such as cones, barrels, delineator posts, rebar chairs, guardrail offset blocks, car stops, etc. The use of temporary fencing made from recycled plastic for construction site safety and snow fencing recently has become common practice. Plastic lumber has been in use for several years in non-structural applications (for example, picnic benches, landscape timber, etc.), in part because it has a much higher life expectancy than ordinary lumber. Plastic lumber is less susceptible to rotting and insect infestation, is more durable, does not splinter and is not considered to be hazardous material. It also can be recycled, unlike pressure-treated wood. In recent years, significant advances have been made in the structural properties of plastic lumber, making its use beyond non-structural applications more promising. ASTM is currently developing standard specifications for plastic lumber products. Designers have also been experimenting with the use of recycled plastic content piles in marine environments where treated wood piles have not performed satisfactorily due to problems with rot and marine life (such as marine-borer worms).

Glass. Mixed-colored recycled glass that is ground into cullet can be used as aggregate for many applications including asphalt cement pavement, pipe backfill, embankment fill and in reflective traffic paint. Glasphalt — asphalt cement concrete containing processed glass aggregate (PGA) — has been successfully used in the United States and Canada on low-volume or low-speed roads. Experience shows that PGA in asphalt cement pavement is acceptable up to a maximum of 15 percent by total aggregate weight, but should not be used in wearing or surface courses.[14]

Compost. The major application of compost is along highways as mulch, blended topsoil replacement, commercial fertilizer supplement and as a soil amendment. The compost is mostly derived from leaf and yard waste, but may also be produced from other fractions of

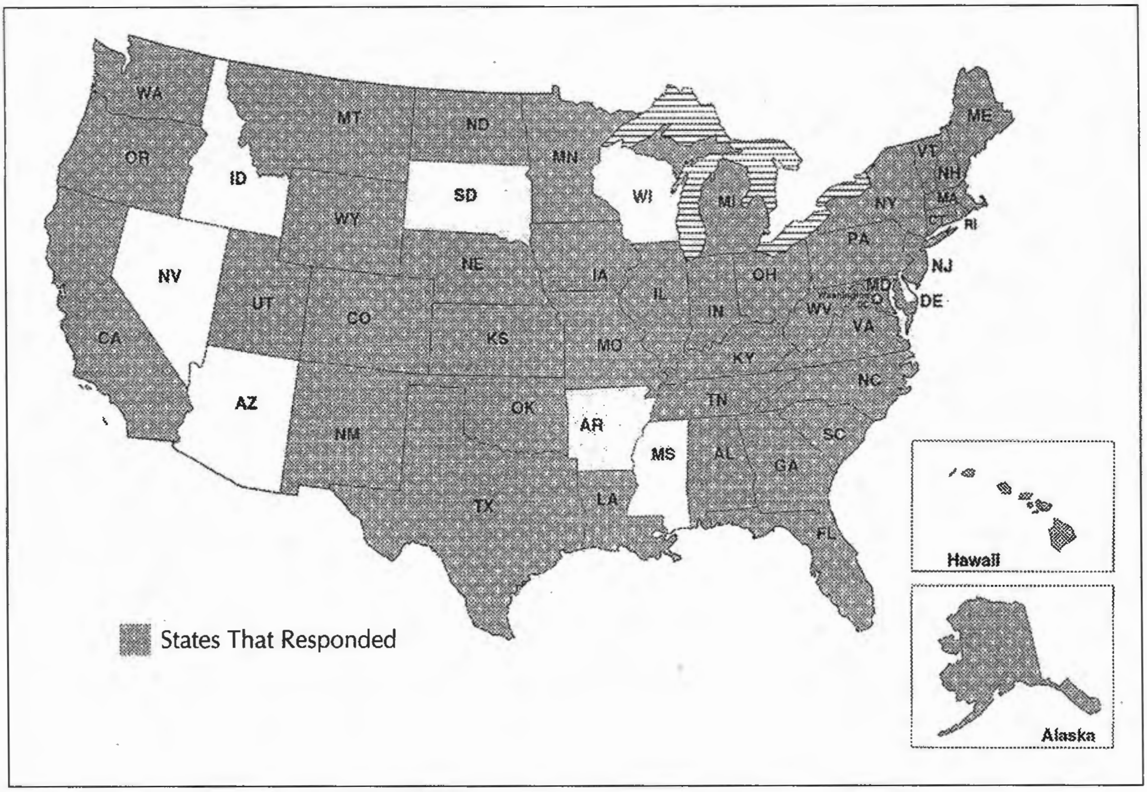

FIGURE 2. States that responded to the DOT questionnaire on WRM use.

the municipal solid waste stream. In addition, it may be derived from agricultural waste (manure and crop residues) and domestic wastewater sludge (biosolids). Recently promulgated federal and state regulations ban the disposal of leaf and yard waste in landfills, and as a result many towns and cities have separate stockpiles for leaf and yard waste that can serve as a source of compost. Furthermore, the number of municipal biosolids composting facilities has grown significantly in recent years to over 200 facilities as of 1994.[15] The use of compost in highway construction is becoming increasingly common because of concerns over the depletion of natural topsoil and the fact that leaf and yard waste, as well as wastewater sludge, represent a significant portion of the waste stream. However, concerns over the quality of compost have been a deterrent to its use. As a result, several organizations (for example, the Council of Northeastern Governors) have been active in the past years in developing standards for the use of compost in highway construction applications.

Blast Furnace & Steel Slag. Blast furnace and steel slag are waste products of iron and steel production, respectively. Blast furnace slag consists primarily of silicates and aluminosilicates of lime, while steel slag contains fused mixtures of oxides and silicates such as calcium, iron, unslaked lime and magnesium. Their most common use is as an aggregate for base courses, asphalt cement concrete and Portland cement concrete. Air-cooled blast-furnace slag in particular has been a well accepted source of aggregate for many years.[1]

Others. Many other WRMs have been used, or are currently in experimental use, for highway construction. Flowable fill, which has become a very popular replacement for compacted soil in trench excavations, has typically contained fly ash and there are now experiments being conducted using waste foundry sand as the aggregate. Pre- and post-industrial shingle waste have been ground and added to the drum-mix during the production of asphalt cement concrete. Most waste metals, particularly steel and aluminum, are recovered and re-

TABLE 2.
Number of State DOTs Actively Using Waste & Recycled Materials

Waste & Recycled Material	Number of State DOTs Actively Using	Number of State DOTs With Specifications
Recycled Asphalt Cement Concrete	40	34
Recycled Portland Cement Concrete	32	31
Coal Combustion Fly Ash	32	30
Scrap Tires	31	23
Blast Furnace Slag	19	21
Glass	14	13
Steel Slag	13	15
Plastic	13	4
Paper	8	5
Compost	6	4
Roofing Shingles	5	2
Others	7	3

Notes: These data were taken from a survey that was conducted in 1995. The total number of responses to the survey was 42 states.

used for the production of new metal products. Other WRMs that have potential for highway construction include carpet fiber waste, petroleum-contaminated soils, municipal solid waste incineration ash, paper products and wood waste.

Current State Departments of Transportation Use

In 1995, a questionnaire requesting information on the use of, and specifications for, various WRMs in highway construction was sent to all fifty state DOTs. Responses were received from 42 states as shown in Figure 2 (on page 11). The questionnaire data reveal that most states are actively using and experimenting with WRMs (see Table 2 and Figure 3), with some of the most commonly used WRMs being:

- Recycled asphalt cement concrete;
- Recycled Portland cement concrete;
- Coal combustion fly ash; and,
- Scrap tires.

Many states have developed specifications for the use of these WRMs and for other less commonly used WRMs. Typically, the number of states using a WRM is greater than those that have specifications due to the fact that most state DOTs prefer to develop a significant level of experience with a material before approving a specification.

In addition, some items (such as plastic products) generally do not have standard specifications but rather are part of an approved products list that state DOTs develop to indicate specific manufactured items that are allowed to be used on their construction projects. In terms of applications (see Table 3), the most common use of WRMs is as an aggregate in base and subbase layers, and in asphalt and Portland cement concrete.

When analyzed by geographic region, the northeast appears to be the most active in the use of WRMs in highway construction, with the level of activity decreasing towards the west and south. This distribution may be due to the higher population densities and older infrastructure generally found in the north and east, which lead to higher disposal costs and a consequent increase in motivation to recycle. In addition, some WRMs have strong regional usage. For example, blast furnace slag is almost exclusively used in the northern and eastern regions (where most of the nation's iron is produced). Additional details on the survey and its results are presented in DeGroot *et al.*[16]

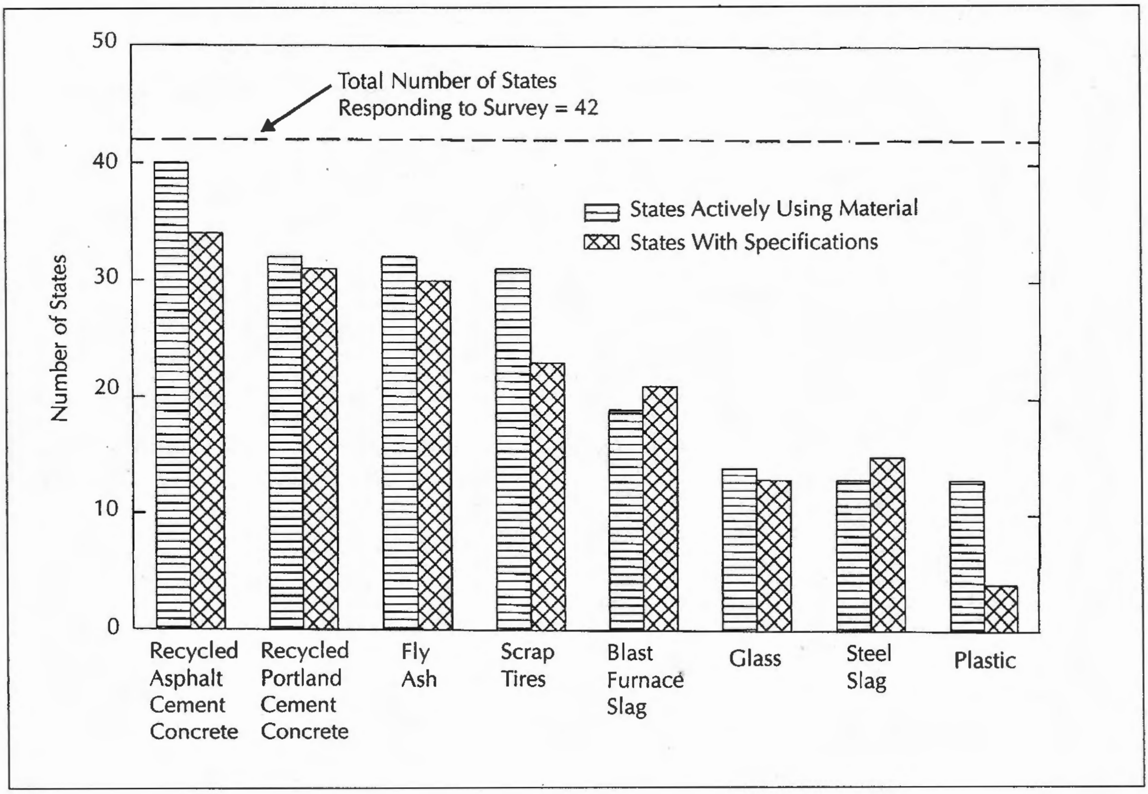

FIGURE 3. Most common WRMs used in highway construction by state DOTs.

Current Massachusetts Highway Department Specifications

All MHD construction practices and materials typically must conform to standard specifications issued by the department. The most recent version of these specifications include the 1988 *Standard Specifications for Highways and Bridges* (the so-called "blue" book) and its 1994 *Supplemental Specifications for Highways and Bridges*. MHD has been actively involved in the use of WRMs in their construction and maintenance operations, and currently has specifications for:

- Recycled asphalt cement concrete for use as an aggregate in new asphalt cement concrete (up to 40 percent by weight of aggregate depending on the process used) and as a base course material (up to 100 percent if it meets the physical properties required of virgin aggregates);
- Fly ash in Portland cement concrete (substitute up to 15 percent cement by weight), and controlled density fill (varying percentages depending on intended use);
- Processed planting material (*i.e.*, compost); and,
- Processed glass aggregate (up to 10 percent by weight of aggregate in new asphalt cement concrete and subbase).

MHD has also used other WRMs that have not yet had specifications approved or that are still considered experimental — including scrap tires for crumb rubber modified asphalt cement concrete and stress absorbing membrane interlayer, compost, recycled Portland cement concrete, plastic lumber, blast furnace slag and guardrail offset blocks.

In addition to the standard specifications, the MHD's Research and Materials Division compiles a list of approved materials, products and manufacturers or suppliers that can be used by contractors and project managers on state highway construction projects. The approved products list covers many miscellaneous construction items that can contain a recy-

TABLE 3.
Most Common Applications of WRMs Base on State DOT Use

Waste & Recycled Material	Application	Number of State DOTs Using
Recycled ACC	ACC aggregate	36
Coal Combustion Fly Ash	PCC	23
Recycled PCC	Aggregate for base, subbase, etc.	22
Recycled ACC	Aggregate for base, subbase, etc.	13
Scrap Tires (Crumb Rubber)	ACC binder (wet process)	13
Recycled PCC	PCC aggregate	8
Glass	ACC aggregate	8
Glass	Base course aggregate	8
Scrap Tires (Crumb Rubber)	ACC aggregate (dry process)	8
Blast Furnace Slag	PCC aggregate	7
Blast Furnace Slag	ACC aggregate	7
Coal Combustion Fly Ash	ACC	7
Recycled PCC	ACC aggregate	6
Steel Slag	Asphalt cement concrete aggregate	6
Compost	Topsoil upgrading, turf establishment, & landscaping	5

Notes: These data were taken from a survey that was conducted in 1995. The total number responses to the survey was 42 states.
ACC = asphalt cement concrete; PCC = Portland cement concrete.

cled content — including joint sealers and fillers, traffic attenuators, traffic cones, highway workzone barrels, sign posts and flexible delineator posts.

Other organizations in Massachusetts are also actively involved in the use of WRMs in highway construction and maintenance. The Massachusetts Turnpike Authority has been using animal manure for a number of years as a soil amendment. The manure is first tested for basic organic/nutrient content to determine if any additives need to be used to improve the source material (for example, lime to increase pH), then it is mixed with a sandy soil and stockpiled for use as a direct soil amendment or as a soil bed amendment. Many town departments of public works in the comonwealth have also been active in the use of WRMs, with the most common ones involving the use of recycled asphalt pavement, recycled plastic items such as cones and barrels, compost, and scrap tires for asphalt pavement and stress absorbing membrane interlayer. In many cases, the towns refer to MHD's standard specifications when specifying these items in contract bids.

Summary & Conclusions

In the 1994 Massachusetts Solid Waste Master Plan, the Massachusetts Executive Office of Environmental Affairs and DEP reaffirmed the goal of recycling and composting 46 percent of municipal solid waste generated within the state by the year 2000. A necessary component of achieving this goal is to develop sustainable markets for waste and recycled materials that are diverted from traditional disposal methods such as landfilling. The transportation industry has been identified as such a market. Some waste materials such as recycled asphalt cement concrete have been successfully used for years by transportation agencies, and many others have the potential to be used in significant quantities. However, it is important to recognize that most WRMs are not common construction materials. Each must be carefully investigated through laboratory testing and field trials to evaluate their physical and chemical properties, environmental impact, constructability, and initial and life-cycle costs.

Results from a survey of state DOT practices show that many states are actively using and experimenting with waste and recycled materials in their highway construction and maintenance programs. The most common application for waste materials is as an aggregate in base and subbase layers, and in asphalt and Portland cement concrete. Some of the most commonly used waste and recycled materials are recycled asphalt cement concrete, recycled Portland cement concrete, coal combustion fly ash and scrap tires. Of these materials, scrap tires use is still controversial because of both technical and cost concerns. As a result, many organizations are actively investigating the use of scrap tires in highway construction, and it may be sometime before the issues of concern regarding its use are resolved.

Some materials — such as blast furnace slag and steel slag — have strong regional usage in and around where these waste materials are generated. Other materials — such as glass, plastics and compost — are becoming increasingly common, with many state DOTs recently adopting standard specifications for their use. Of these materials, compost has the greatest potential for growth since the waste material it is produced from (*i.e.*, yard waste, biosolids, animal manure, etc.) is a significant portion of the waste stream and because it has many potential applications in the establishment and maintenance of vegetative growth along highway rights-of-way.

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Dredging Design & Hydrographic Surveying

Automated hydrographic surveying presents a more accurate means of acquiring data needed for the design of navigational channels and other dredging projects.

JOHN A. DERUGERIS

Navigation projects essentially build roads, or channels, within a waterway to allow the passage of vessels during all or most tidal cycles. The design of navigation channels incorporates several critical factors. Channel widths and depths vary immensely depending on the size and number of vessels for which they are intended. For instance, a channel leading into a small marina may only need to be 50 feet wide and 6 feet deep, whereas a channel into an oil terminal may need to be 600 feet wide and 40 feet deep. It is important to remember that the shallowest point in any part of a waterway becomes the controlling depth for the entire channel.

When a channel is designed or improved, its configuration is also of significant importance. The alignment should always be as straight as the topography will allow. Turns, especially sharp turns, should be kept to a minimum. A mariner cannot see the channel outline since it is beneath the water, and generally has only a few navigation markers and possibly a chart for guidance. Since boats swing and rotate as they turn, it is also important to consider that turning points need to be wider than the channel itself. Generally, "short-cutting" the inside corner provides sufficient turning area.

When considering channel width, it must be determined how easily boats will be able to pass in opposite directions. The designer must keep in mind that conditions — such as fast currents, rain, fog and heavy seas — will reduce a mariner's ability to control a vessel in a confined area. The design requirements of recreational and commercial waterways normally fall within known parameters. However, when designing or modifying channels that handle heavy shipping traffic, the task is far more critical. In these cases, traffic and other navigation conditions are often modeled using computer simulations that will graphically display the conditions a vessel might expect to encounter in a variety of situations.

Design channel depth is always based on the low water elevation as established by the National Oceanic and Atmospheric Administration (NOAA), and is determined by taking the sum of several factors. Some of the factors that are considered are:

- The draft of the vessels for which the channel is intended;

TABLE 1.
Typical Dredging Costs (1997)

Dredging Method	Dredged Material	Channel Depth	Disposal Method	Cost ($/cubic yard)
Maintenance Dredging (Bucket or Hopper)	Loose Sand or Mud	Deep Draft	Offshore	3.50
Bucket or Hydraulic	Sand or Gravel	Moderate Draft	Inshore	7.50
Hydraulic Excavator	Shale, Rock (Ripped)	Moderate Draft	Inshore	25.00
Bucket	Lightly Contaminated Silt	Moderate Draft	Landfill	30.00
Bucket	Lightly Contaminated Silt	Moderate Draft	Stabilize with Cement	50.00
Hydraulic Excavator (Drill & Blast)	Rock	Moderate Draft	Inshore	75-100
Bucket/Hydraulic	Contaminated Silt	Moderate Draft	Confined or Resource Conservation Recover Act (RCRA)	100-1,000

- An allowance for clearance from the keel of the intended vessels to the dredged bottom;
- An allowance for astronomical low tides;
- An allowance for sea state (waves);
- An allowance for shoaling; and,
- An allowance for inaccuracies in the dredging process (overdepth).

Another major design and planning issue of any navigation project is the cost, which must be weighed against the economic benefits that will be derived from the project. Costs are related to the size, type and availability of dredging equipment, the character of materials to be dredged and the disposal requirements. For example, a deep-water channel that is accessible to large dredging equipment will be less expensive to dredge per unit cost than a site that has only a few feet of flotation available, thereby limiting it to smaller equipment. General equipment access issues that significantly impact costs are:

- Bucket dredged channels less than 100 feet wide;
- Bucket or hopper dredged channels less than 12 feet deep;
- Hydraulic dredging projects requiring pipelines over 6,000 feet in length;
- Hydraulic dredging projects with less than 4 feet of draft available;
- Waterways with bridge restrictions under 60 feet in height or width; and,
- Hydraulic or bucket dredging projects exposed to fast currents, swells or heavy seas.

The nature of the materials to be dredged also affects both the excavation and the disposal costs. For example, silt is very inexpensive for a dredge to excavate, and can be pumped much longer distances, but is far more costly to contain, dewater and dispose. Conversely, hard packed sand and/or gravel can be more expensive to excavate and will cause severe wear on parts, but has many potential reuses (including possible resale).

Glacial till and ledge rock can escalate costs of a navigation project dramatically. Ledge rock normally requires drilling and blasting, which may be frowned on by environmental groups, especially if the blasting is near the habitats of any endangered species. If the rock is fractured or if boulders in glacial till are not too large, hydraulic excavators can sometimes be employed to rip and otherwise excavate these materials without blasting. Sand, gravel and rock rarely contain significant levels of contaminants, therefore their reuse and disposal options are far less restricted. Some of these costs can be offset by processing the materials and selling them. However, the success of such activities requires experience in mining and quarrying operations, and the availability of space for processing. Table 1 shows typical dredging costs in 1997.

The overdepth and side slopes of a dredged channel are also important design considerations (see Figure 1). Overdepth is an increased depth allowance that compensates for natural inaccuracies inherent in the dredging process. The overdepth is usually predicated on the size of the dredge to be employed and the "sea-state" conditions under which it must operate. With very little exception, any dredging process leaves "ridges" in the finished bottom. Depending on the equipment, the height of these ridges can range from 6 inches to 2 feet.

The finished channel depth — and, thus, the controlling depth — is based on the tallest peak of the ridges (see Figures 1 and 2). The valleys between these ridges then become excess dredging. This additional dredging is not wasted, however, because these pockets act as a limited storage area for future shoaling. In fact, in areas of highly concentrated shoaling accumulation larger pockets (or basins) are sometimes excavated to provide additional storage.

The steepness of a side slope is a function of:

- The stability of the native soils; and,
- The rate of sediment accumulation at the toe of the slope.

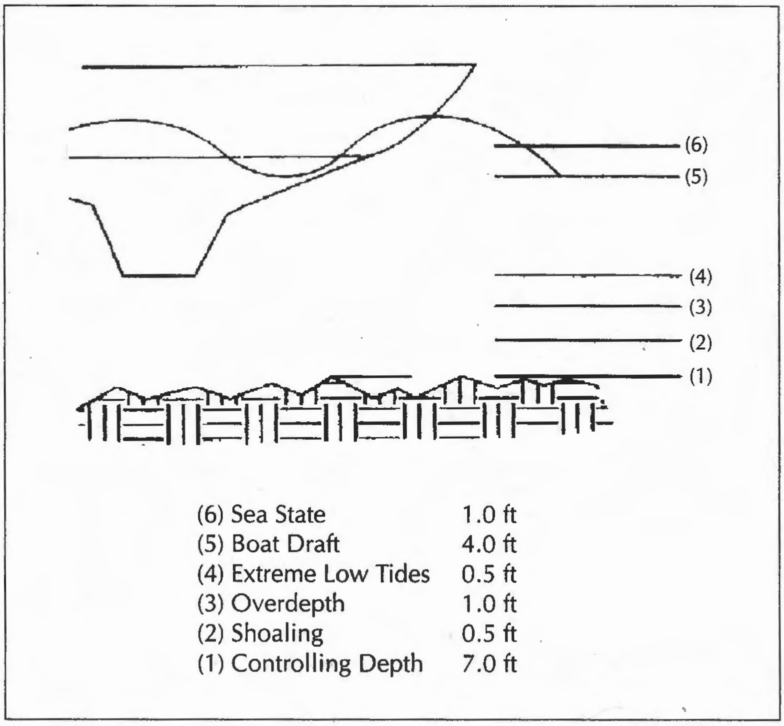

FIGURE 1. Determining channel depth.

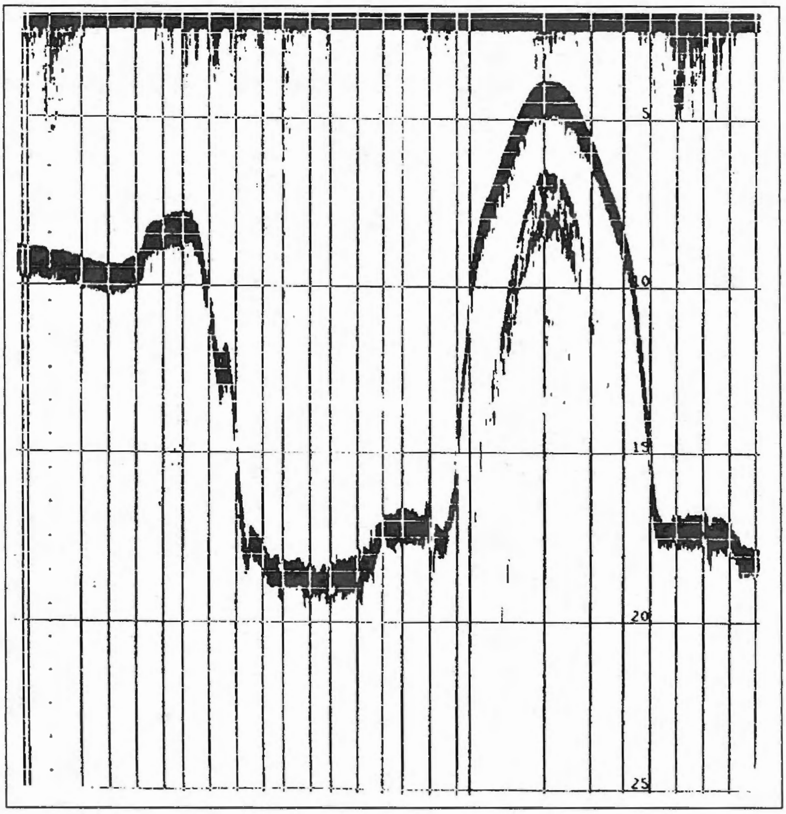

FIGURE 2. Typical fathometer chart readout showing ridges.

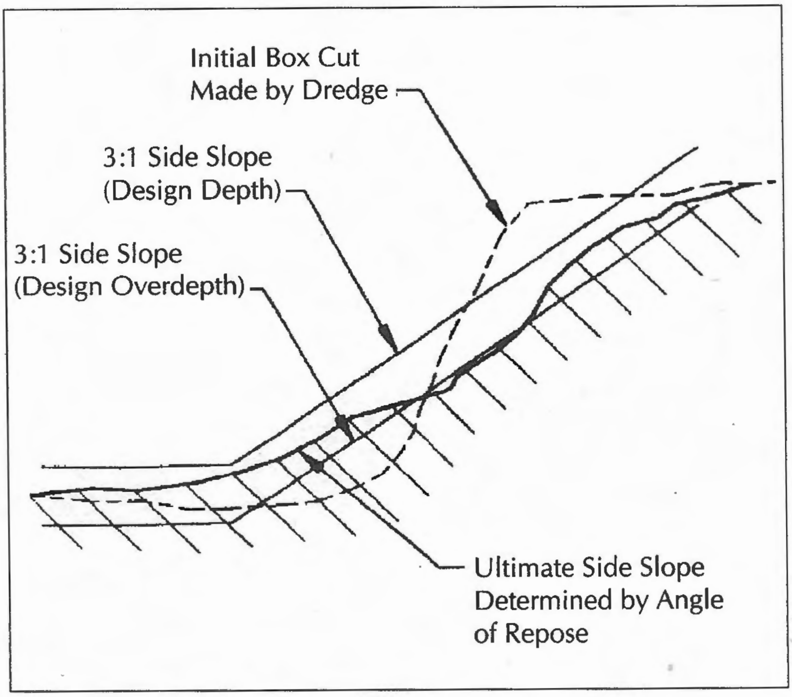

FIGURE 3. Side slope determination.

Most federal regulations for channels specify a minimum of a three (horizontal) to one (vertical) side slope (3:1) to transition from the channel limit (or toe) up to the pre-existing grade. It is a common misconception, however, as to how these slopes are actually formed. In reality, dredges are not designed to cut trimmed side slopes such as those on an embankment.

Instead, slopes are compensated for by overdigging into half of the side slope area at the full dredge depth — a process also known as "box-cutting" (see Figure 3). The remaining bank then collapses at its normal angle of repose and forms the slope. Slopes flatter than 3:1 are used where there are fast currents, very soft sediments or where additional storage space is needed due to high shoaling or littoral transport occurring at the toe of slope. Because the formation of dredged side slopes is a function of the random stability of the soils at any given location, the final sloped face is generally extremely irregular.

This irregularity presents a problem when surveying and/or calculating quantities of dredging, because a surveyed cross-sectional view of the slope can normally differ significantly between sections taken as close as 10 feet apart. The density of the soundings are a governing factor in determining the accuracy of the finished work product (*i.e.*, a tight grid of 5 feet by 5 feet will yield a more accurate picture of the slope than a grid of 25 feet by 10 feet). Furthermore, in order to accurately define steep slopes, the surveyor must be sure to employ a narrow transducer beam. The cost effectiveness of using the beam is closely tied to the height of the side slope above the channel bottom and the unit cost of the associated dredging. For example, a hopper dredging project with a short haul distance might have a unit cost of $3.00 per cubic yard. If the dredge cut for this project is in the range of 4 feet, then the total discrepancy might be 1,500 cubic yards per mile of channel. The cost to survey and analyze this area would outweigh any potential savings. Conversely, on a project such as the Arthur Kill River in New York (where the side slopes are 25 feet high and dredging costs $40.00 per yard) considerable effort in accurately defining these quantities is certainly warranted.

The importance of following proper design methods increases exponentially with the size and number of vessels using the waterway. The designer must have enough data and experience to visualize the channel both while in use as well as the consequences if the design is inadequate and a mishap occurs. As with highways, a poorly designed channel could cause accidents such as a grounding (possibly injuring a mariner) or a spill that may damage the environment. Obviously, the size and number of vessels using a channel is a major factor in putting these potential accidents into perspective. If a small recreational boat were to go aground because a channel is poorly designed or maintained, it may require no more than the assistance of another passing boat and possibly repairs to its propeller. Conversely, the grounding of a larger vessel, such as a fishing boat or barge, may have other serious consequences such as loss of life, injury, oil spillage or serious structural damage.

Disposal Options

Disposal of dredged materials from navigation projects is an increasingly important issue. Disposal options are typically related to the character of the soils being dredged. Up until recently, most dredge materials, regardless of their composition, were disposed of in off shore dumping grounds, or in upland diked containment areas, and non-navigation projects such as beach nourishment were "mined" from nearby designated underwater borrow pits. In recent years, environmental regulations have changed these processes and their associated costs drastically. All offshore disposal sites are now closely baseline monitored against potential environmental impacts for everything from contaminants to sediment excursion. Before any dredged materials are authorized for disposal by this method they are closely screened for potential contaminant content (by chemical analysis) and potential hazard to marine organisms (using bio-assays).

Upland confined disposal sites suitable for dredged soils have come into extreme short supply for a number of reasons, including environmental mitigation and coastal development. Environmental regulations often require that materials be stored temporarily, dried, possibly treated then retransported to other permanent locations. Upland/inland confined sites have their own set of problems. Recent concerns regarding possible contamination of aquifers with everything from salt to trace chemicals may require a disposal site to be sealed with an impervious liner.

These issues have caused the development of alternative disposal concepts that are more environmentally acceptable. If soils to be dredged are sandy and/or "clean," they can be reused for beach nourishment, fill or for the reconstruction of wetlands. Silty soils are far more plentiful, costly and difficult to dispose. These soils can be considered for landfill cover, stabilization with cement for structural fill, supplementing and manufactured into topsoils, and the like. Currently, the cost of these "reuses" raises disposal costs by $10 to $50 per cubic yard.

Shoreline Restoration

Not all dredging projects evolve from navigation needs or other requirements for creating deeper water. Shoreline restoration projects involve the replenishment of soils that have been eroded from coastal shorelines. While it is cost-effective to link the two types of projects, the needs for the restoration or protection of upland coastal resources may be coupled with a location too remote for economical access to a complementary borrow area. The distance of the required transport affects costs directly. The maximum distance will vary considerably in conjunction with the perceived value of the benefit. Common examples of restoration include the nourishment of beaches, bluffs and, to a lesser extent, exposed marshes or other wetlands.

Beaches. Beaches and upland shorelines exposed to severe waves generally require periodic replenishment with clean granular soils (see Figures 4 and 5). Contrary to some environmental policies, unless the eroded area is to be protected by a physical structure (such as a seawall or revetment), it is important that the nourishment material be of sufficient grain size to withstand normal erosive forces. The residual soils on a beach often bear little resemblance to the original soils.

To properly assess the material requirements (*i.e.*, the grain size) of a nourishment project, the following criteria must be evaluated:

- What soils previously existed at the site;
- What the intended use of the finished project is;
- What soils are available for nourishment, and where they are located;
- Where the new soils will migrate, and what secondary effect they will have; and,
- What minimum grain size will withstand routine erosive forces.

Typical tests that are run on soils to determine their suitability for this use are size

FIGURE 4. Beach nourishment at Cole River, Swansea, Mass.

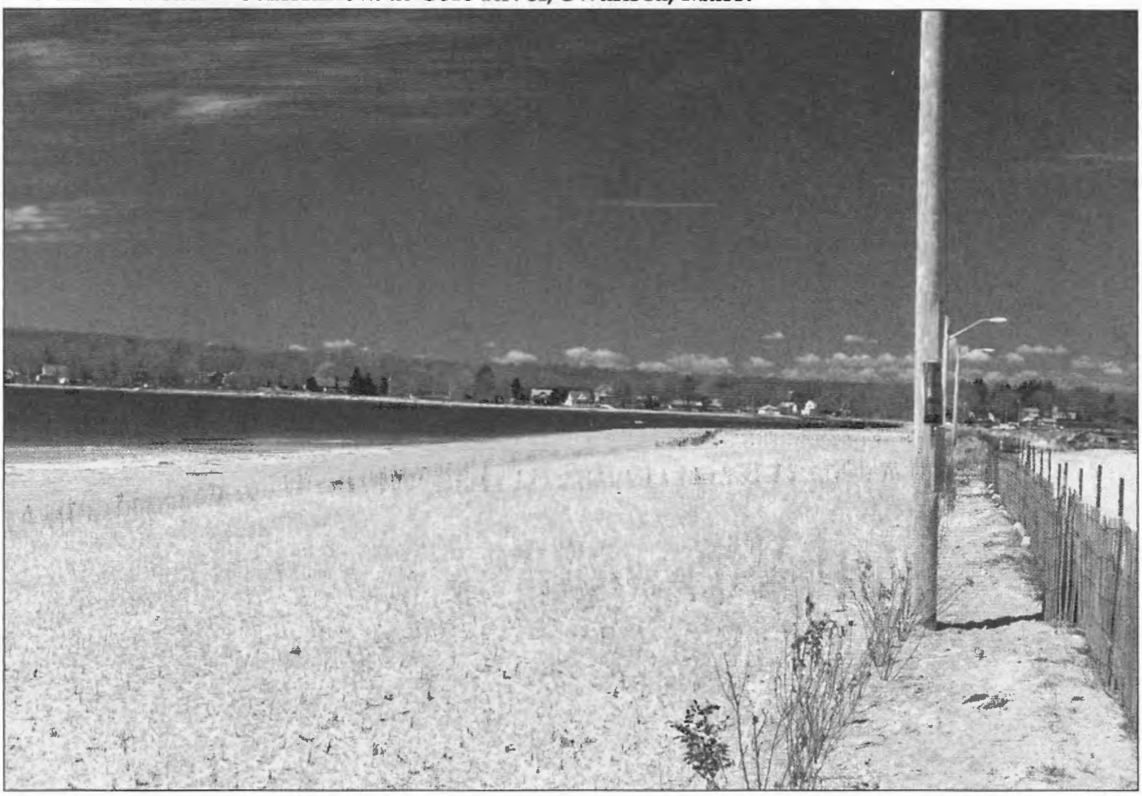

FIGURE 5. Completed beach nourishment at Cole River, Swansea, Mass.

fraction gradation and chemical contamination. Because of the direct disposal of effluent water from the hydraulic filling process into the adjoining waterway, allowable contaminant levels closely follow those for offshore disposal.

It is generally not cost-effective or environmentally desirable to have a shoreline nourishment project erode away after a few storms or one season. If nourishment fill is to remain unprotected (*i.e.,* without a protecting physical structure such as rip-rap), the slope of the new fill approaching the water becomes very important. Flat slopes (20:1 or flatter) are far more effective at dissipating erosive wave energy than steep slopes.[1]

The designer must also consider the effects of short-term erosion on the particular site during the nourishment process (see Figure 4). Most beach nourishment projects are performed using hydraulic dredges. This type of equipment requires the use of large volumes of water to transport the sand from the area where it is "mined" to the area where it is to be placed. The water used in the transport process normally erodes the area immediately ahead of the fill. Caution and experience are required to determine the nourishment methodology when hydraulic fill is placed in the vicinity of unprotected structures (such as roads or houses) since undermining may occur.

The cost effectiveness of a beach nourishment project is directly proportional to the proximity and exposure of the source of compatible, granular soils. If hydraulic placement is used, the designer must consider the availability of dredging equipment that can effectively operate in the borrow area, as well as the distance the material must be pumped.

Costs dramatically increase if the pump transport distance exceeds 5,000 feet, or if the potential for wave action in the borrow area exceeds 2 to 3 feet. For example, if the dredge area is exposed to heavy seas, the dredge must be sized to work under those conditions, thereby limiting the number of dredge companies able to compete for the work to one or two. Otherwise, the dredge would have to be moved to safe harbor whenever weather conditions deteriorated, resulting in a significant amount of non-productive time. Both scenarios translate to higher costs.

Wetlands Restoration. Man-made wetlands are rapidly becoming an attractive alternative for the disposal of dredged materials. These projects are commonly limited to the replacement of marshes that have been recently lost to erosion. Projects that create new wetlands to replace historic habitats, however, are not uncommon. Soil gradation requirements for these projects are usually far more forgiving than beach nourishment projects. Wetlands have been restored using everything from the finest of silts to coarse gravel, but it is advisable to consult with an expert in the field of wetland grass planting when planning a specific project.

If fine sediments (such as organic silts and clays) are to be used for the fill, diking of some form is required to retain the soils. These confinement structures must be sufficient to protect the fill from erosive forces for the anticipated life of the project. Fine sediments retain excess water far longer than sandy soils (months versus hours), thus there must be adequate area for the decanting of the effluent water. Sediments will naturally dewater themselves over time and consolidate if they can be "surcharged" above the low tide zone by their own weight. Final elevations should be as high as the planned wetland vegetation will tolerate to facilitate the surcharging effect. Building the initial grade above the final grade is generally desirable since the fill will settle considerably over time, allowing more complete inundation. Building a wetland fill that must be completely inundated at all times is considerably more difficult, since the submerged weight of the surcharge is dramatically reduced. In this case, grain size must be considerably coarser and the percentage of silts must be lower. Unless some form of temporary surcharge can be placed, the fill will take several years to attain a consistency no better than pudding.

Pond/Lake Restoration

Dredging projects in ponds, lakes and reservoirs are generally designed to increase storage capacity that was lost due to the accumulation of sediments. Environmental enhancement can also be achieved, since oxygen depletion from

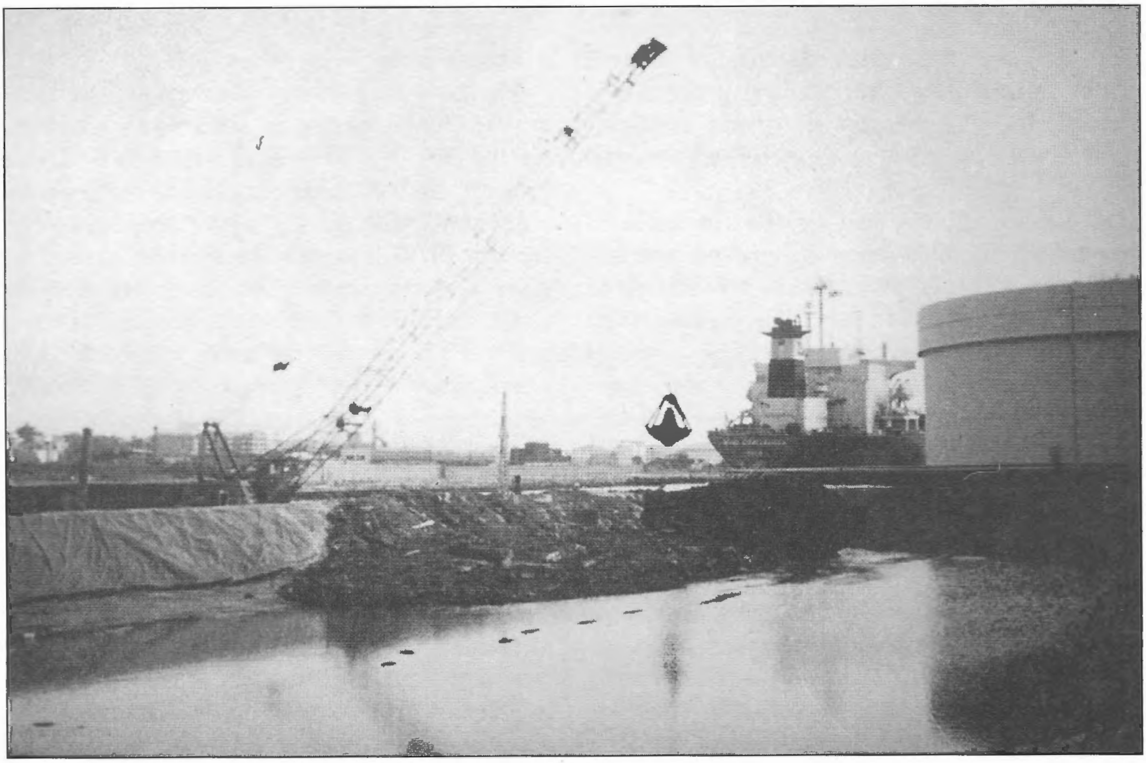

FIGURE 6. A confined upland disposal site.

organic deposits can also be reduced. These sediments are often contaminated and must be dealt with accordingly. A follow-up to any planned dredging of an inland resource should include a study of methods to mitigate future sediment intrusion processes.

Small ponds with perimeter access can be dredged by dragline or clamshell cranes from the shore. On larger ponds where perimeter access is limited, hydraulic dredging is the next most cost-effective method, since larger bodies of inland water will rarely accommodate floating clamshell dredges and the support vessels. Hydraulic dredging can be cost-effective if there is sufficient space available to build a diked disposal area. If the soils to be dredged are fine sediments, a large storage area is required to permit the natural decanting of water and, ultimately, drying. Costs rise dramatically if storage capacity is limited and flocculates or mechanical dewatering devices must be employed.

If dredging must take place in a reservoir or public water supply, turbidity becomes a serious concern, especially if the sediments to be dredged are contaminated. Turbidity during a dredging project can come from sources other than the dredge itself. For example, if the existing depths of the body of water are extremely shallow, other sources of turbidity must be evaluated. For instance, if the smallest tender boat for a dredging plant requires at least 2 feet of flotation to operate, under such conditions these boats can create more turbidity than the dredge itself if they do not have sufficient water depth in which to navigate.

Contaminated Sediment Clean-Up

Most contaminants tend to attach themselves to the fine sediments, consequently complicating underwater remediation projects. When dealing with serious contaminants, all of the considerations previously discussed apply at least ten-fold, since costs generally multiply themselves by at least that much. An enforcing agency will often dictate the method of dredging, which is predicated on the protection of the environment, even though the method may not be efficient. The volume of water that the dredge generates during the process becomes extremely important since decanting areas normally need to be sealed or lined to prevent the leaching of contaminants into clean soil.

Furthermore, effluent water may require flocculation or extensive treatment to prevent recontamination of the waterway. If the materials must be transported to a remote site (such as a licensed disposal facility), mechanical dewatering is commonly required (see Figure 6). Turbidity is such a critical concern on some projects that it has prompted the development of new low-turbidity dredging systems.

Site Analysis

As in forecasting weather, the design of a dredging project is still more of an art than an exact science. On complex dredging projects the designer must have a "feel" for the idiosyncrasies of each soil condition and stratification present, and how each will act when its unique balance is upset. Management of critical issues (such as disposal and turbidity management) are still in the development stages and, therefore, are far more difficult to assess. Unfortunately, there are few reference libraries that can accurately predict every possibility of combinations. Therefore, the individual experience factor is of primary importance on dredging projects.

Determining Existing Conditions: Hydrographic Surveys

In order to properly plan and prepare the design of a dredging project, it is first necessary to obtain basic preliminary data. These data include:

- Background information (such as property plans, navigational charts, current studies); and,
- Information on user requirements (*i.e.*, type and draft of anticipated traffic).

In addition, site-specific data must also be gathered, including:

- Sediment grain size distribution;
- The existence of contamination;
- Critical topography;
- Geology;
- Environmental information; and,
- Hydrographic data.

The most important data for a successful project are the bottom geology and topography. The planning and design of any dredging project must begin with recent, high-quality hydrographic and bottom coring data. On difficult projects, these data may need to be supplemented with geophysical information such as sub-bottom profiling, and multi-beam or side scan, or magnetometer surveys. In general, the more information the designer obtains during the planning process, the fewer unpleasant surprises turn up when the actual work commences.

The hydrographic survey (sometimes called bathymetry) is a detailed mapping of the "bottom" of a body of water (see Figure 7). There are two formal standards that have been set for bathymetry by the NOAA and the U.S. Army Corps of Engineers (COE). Of these two, the COE Manual EM 1110-2-1003, *Hydrographic Surveying*, is the standard for conducting and processing surveys for navigation and dredging projects.[2] The COE is, by far, the largest contractor of navigation surveys and dredging projects in the United States and, possibly, in the world. As a result, their standards have been built from the ground up, and have withstood considerable scrutiny over the years.

On any federally funded project, the COE also requires adherence to fairly stringent qualification and experience requirements for the field crews, reduction methods and the supervision of surveys. Field crews must be able to demonstrate several years of experience with automated hydrographic systems, and work must be conducted, or supervised, by a licensed engineer or surveyor, as well as a hydrographer certified by the American Congress of Surveying and Mapping (ACSM). If the largest contractor of dredging related work has established and adheres to such standards, it must be cost-effective.

The COE's EM 1110-2-1003 manual further establishes standards of quality for automated and non-automated surveys.[2] Automated surveys, however, have been proven to be far more reliable. Therefore, almost all COE districts no longer use non-automated survey methods.

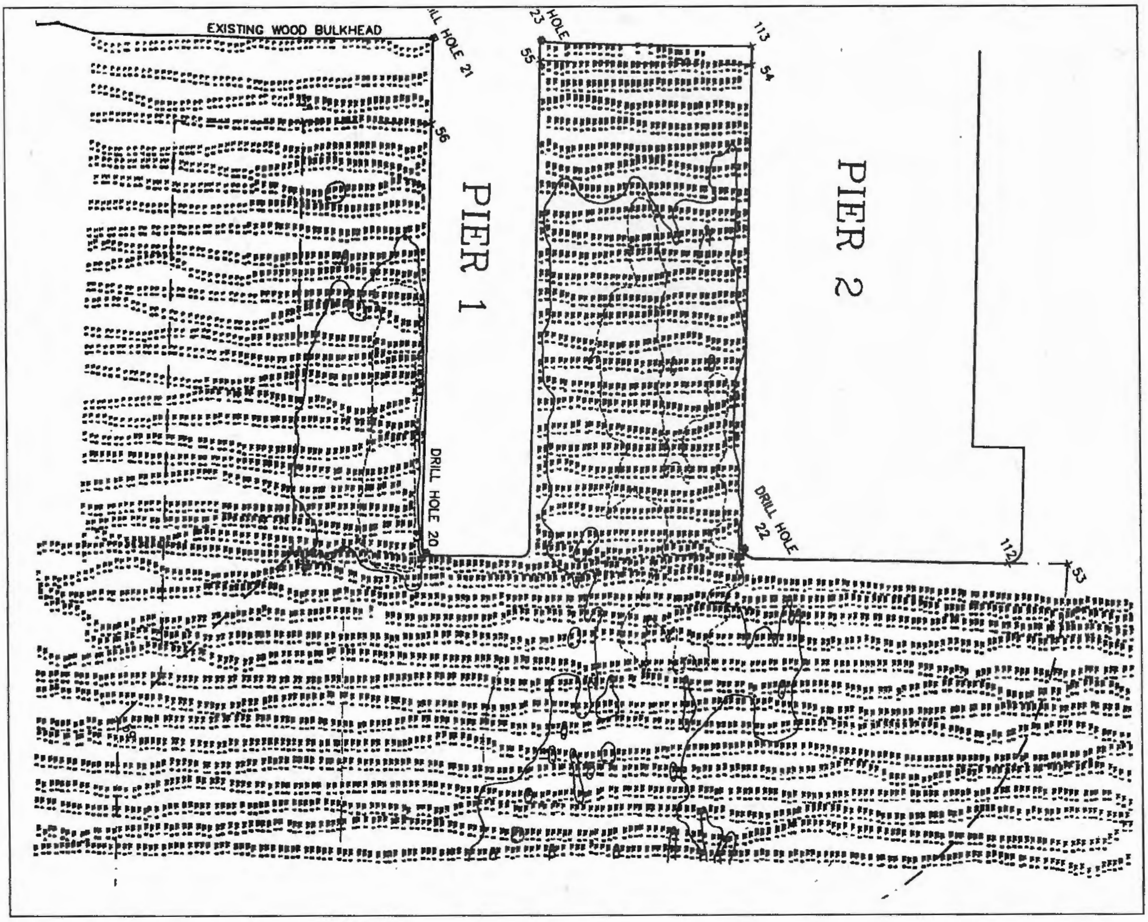

FIGURE 7. Hydrographic survey of Davisville Pier, North Kingston, Rhode Island.

There are several types of automated surveys that can be conducted:

- Reconnaissance surveys (Class 3);
- Condition surveys (Class 2); and,
- Quantity surveys (Class 1).

Of these methods, quantity surveys are the most accurate and are used for planning, as well as for final dredging.

Equipment for Class 1 automated surveys consists of:

- A positioning system capable of producing accurate X-Y coordinates within 1 meter of true position at 1 second intervals.
- A sounder or fathometer capable of recording and digitizing depths with an accuracy of 0.1 feet or less.
- A computer with software capable of producing navigation guidance, as well as filtering and logging data.
- Some systems also utilize electronic compass headings, and in off-shore areas where swells or large waves prevail, heave-pitch-roll sensors are required.

X-Y Positioning. Positioning systems have made significant advances over the past twenty years. Today, the primary systems in use are global positioning systems (GPS), and range azimuth systems. GPS is the most popular where it is practical for use. A high-accuracy GPS, properly set up, can reliably produce positions well under the COE 1-meter standard, and newer systems can reduce potential error to a few inches. In addition, since GPS data can be easily converted to state plane grid systems, it reduces reliance on local control, which is commonly lost. This ability also aids greatly in

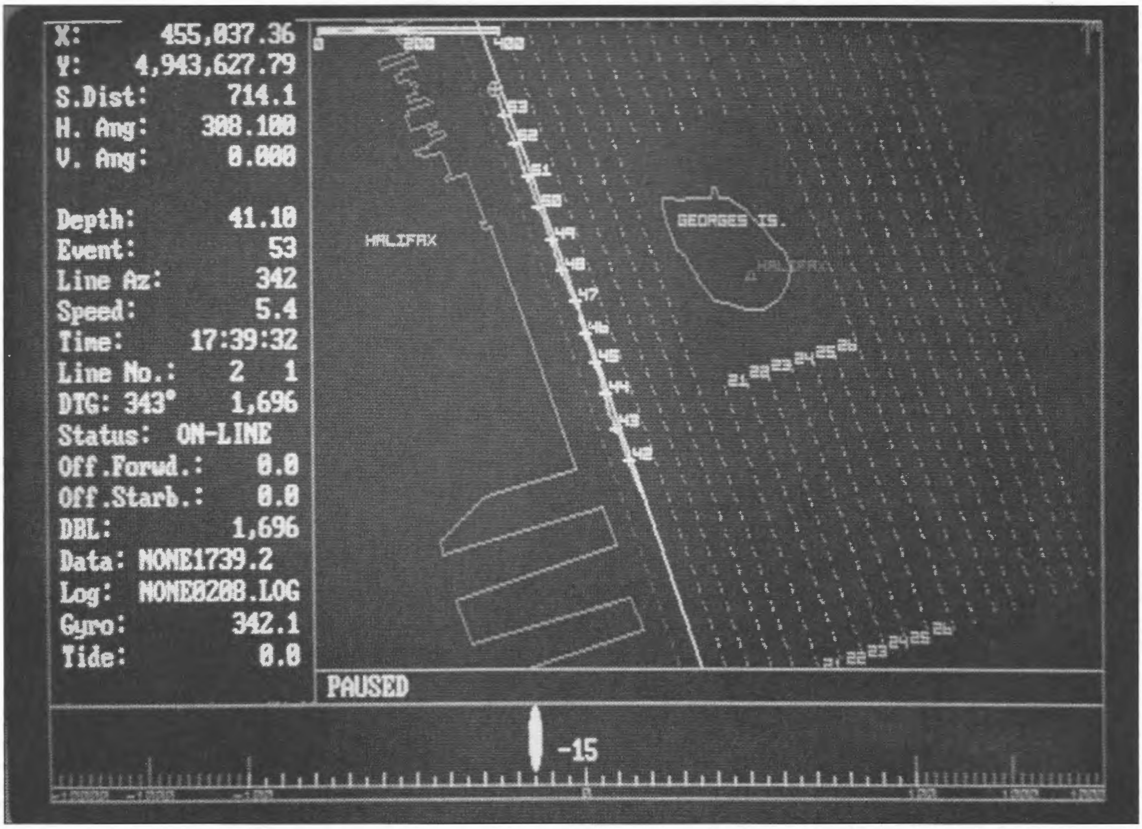

FIGURE 8. Graphical display during a survey.

making any conversions to increasingly popular geographic information system (GIS) networks.

GPS does, however, have serious limitations. For instance, it will not work in enclosed areas such as tunnels or under piers. Some GPS equipment is very susceptible to multipath error from bridges, cranes, passing ships and the like. The biggest problem with any system is the inability to perform final position closure. Therefore, the experience of the field crew becomes critical since they have to be alert for situations that will produce erroneous data.

Depth Measurement. Reliable depth measurement can only be attained through the use of a survey-quality echo sounder. These sounders are rugged, precise instruments, capable of calibration to compensate for variations in water temperature and salinity, and able to measure depths accurately. Costs start at about $15,000 for single frequency and $28,000 for dual frequency echo sounders.

Computers & Software. The onboard computer and software system must precisely unite the positioning and depth data (see Figure 8). Due to the harshness of the working environment, computers need to be ruggedly packaged to protect them from extreme temperatures and moisture. Quality software is very important since it must precisely match position and depth data to within a small fraction of a second. This precision is critical because positioning and depth recording equipment normally run at different speeds. When sounding at the rate of 10 feet per second, a time tagging error of 0.3 seconds will produce a position error of 3 feet. Clear, understandable navigation graphics are also very important. These graphics allow the boat operator to properly cover the survey area without leaving unwanted gaps, and also provide for the proper monitoring of system performance during the survey.

Tidal Correction. The standard procedure for logging tidal data during a survey can be man-

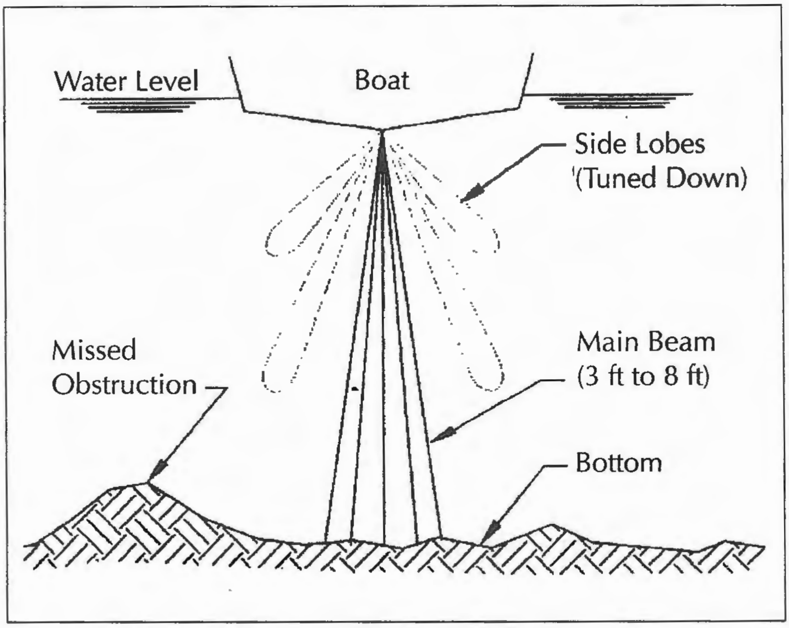

FIGURE 9. Transducer beam pattern.

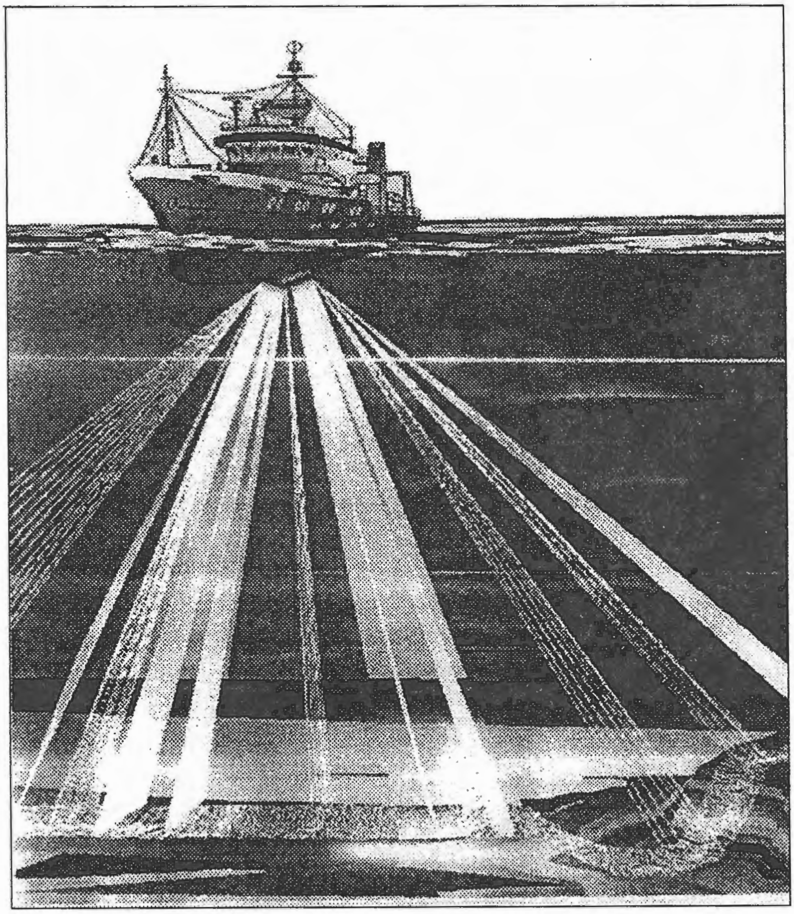

FIGURE 10. A sweep survey.

ual or electronic. For precise surveys, an electronic tide gauge is far more accurate. These gauges function through the use of a pressure transducer placed within a "stilling" tube. When properly installed, this process eliminates all errors induced by wave action and even swells. Further, it creates a date/time versus tide paper chart record of the day's activities that can be referred to at any time. Whether the tide is corrected in real time, or in post processing, is a matter of preference, but it should be done by only one method uniformly within each office to reduce the chances of error.

The newest real-time kinematic on-the-fly (RTK-OTF) GPS equipment also produce elevation outputs accurate to within a few centimeters at rates of five readings per second. This accuracy has proven suitable for providing not only tidal corrections, but also corrections for ground swell heave and vessel squat, which require correlating conversions from ellipsoid height to local datum and networking these data into the hydrographic software. When using this method, however, the tides should still be checked regularly by conventional means since anomalies of up to 2 feet can occur as individual satellites move in and out of range.

Common Problems & Misconceptions

Most inaccuracies that occur

with hydrographic surveys emanate from two sources:

- The use of inadequate, antiquated or improper equipment; and,
- Inexperience of the personnel utilizing the equipment.

Some surveyors still attempt to prepare hydrographic surveys using antiquated means (such as the use of lead lines, sounding poles or even fish finders to obtain depth data), while using two transit or transit/electronic distance measurement (EDM) methods for positioning. Lead lines and sounding poles leave no paper trail, and give no visual picture of what conditions exist between soundings. Fish finders and depth recorders designed for recreational use are routinely too inaccurate to meet survey standards.

Transit cut-in, range positioning and EDM positioning may give reasonable positions on a stationary boat, but a boat can rarely be held stationary while soundings are taken. Two pieces of data — the position as shot and then the sounding — must be recorded. Collecting these data takes at least a few seconds. In that time, a boat can drift several feet. Furthermore, the depth might be recorded with the wrong position, or the depth could be misread or misrecorded. Also, during this measurement process, the boat operator has nothing by which to navigate, thus the resulting surveys always have redundant data in some areas and no data in others. Surveys conducted in this manner have been the source of some of the largest contract disputes.

A common source of error in any hydrographic survey (automated included) is tidal reduction, which accounts for at least 50 percent of all non-method related survey errors. Crews should always check tidal benchmarks and completed tide curves against predicted and observed tidal elevations. Although wind and weather can affect tidal cycles, if the weather is fit for surveying, the tidal cycle will rarely differ more than a few tenths of a foot from the predicted curves.

Another common problem in hydrographic surveys relates to attaining the proper density of soundings. The footprint of a survey transducer beam equates to shining a flashlight on the floor (see Figure 9). At shallow depths, a transducer footprint is less than 1 foot in diameter. In 40 feet of water it will be 5 to 8 feet wide. Although most fathometers record data continuously on a sounding line, unless a sweep system is employed, no data are collected between the lines. For instance, if sounding lines are run at 50-foot offsets, there is a space between these lines of about 45 feet where no data are gathered. For some maintenance dredging projects, this void may not cause much of a problem since shoaling materials are commonly soft. Conversely, on projects involving improvement dredging, obstructions (such as rocks or pilings) can be missed and, if left undetected, become hazards to navigation. Under these conditions, sweep surveys employing sounders with multiple transducers and overlapping coverage are required (see Figure 10).

Low-density material, commonly called fluff (found especially in freshwater ponds after dredging) can give false readings, and is often the subject of disputes. Employing lower frequency transducers (which are available down to 28 kHz) can be used to offset this problem. The low-frequency equipment can see through fluff. However, there is loss of definition since they employ a wider beam angle. Normally, the depths obtained by a low-frequency system need to be compared with high-frequency soundings and lead lines or corings.

Summary

Electronic hydrographic surveying has greatly improved the accuracy and reliability of data over archaic manual surveying methods. It has also created an abundance of new types of data for use in the design of dredging projects. Hydrographic surveying technologies are advancing and improving almost monthly. Capitalizing on these advances requires constant training and a continuing education process. These advances have ushered in a field of highly specialized firms that stay at the forefront of the industry, and have brought a whole new level of service to a field where there is an ever increasing need for high-quality data.

ACKNOWLEDGMENTS — *This article was adapted from course notes and a presentation by the author at the BSCE Waterways, Ports, Ocean and Coastal Technical Group's seminar on "Coastal Community Dredging" in April 1997.*

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Anticipating Global Transportation Concerns in an Ever-Changing Environment

The success of meeting the world's transportation needs in the next century resides in how well engineers meet the challenge of continual change.

RICHARD R. JOHN

Beware of technological solutions looking for problems. Experience has shown that technology is rarely a controlling factor in bringing about transportation innovation. Other issues — institutional, political, economic, financial and social — weigh heavily in today's intricate transportation decision-making processes. When a new transportation concept is introduced — be it monorail, levitated vehicles or anything else — always ask the simple questions:

- Who are the passengers?
- Where is the right-of-way?
- From where will the funding to pay for the project come?

A Growing World

The traditional theories and concepts about the position of the United States in the world are changing drastically, and at an ever-accelerating rate. The world population is currently 5.7 billion people (and growing) and becoming more urbanized. Tokyo, with 30 million people, is larger than 162 countries. Since 1960, Bangkok's population has tripled in size to 7.1 million. Asia's urban population will increase by 600 million during the next twenty-five years.

In his book, *Megatrends Asia*, John Naisbitt states that "at six minutes past midnight on December 6, 2006, the human being will become primarily an urban animal."[1] In other words, more than half of the projected 8 billion people in the world will be living in cities, many in megacities with populations approaching 30 million, and with names and places not normally in the evening news — Karachi, Pakistan; Dhaka, Bangladesh; Hyderabad, India; Sao Paolo, Brazil; and Lagos, Nigeria — to name a few.

Although the new market prospects are enormous, the resulting urban congestion will place profound strains on the world's environmental, social, political and economic systems. The need for basic transportation infrastructure and transportation financing will be acute.

Today, nearly 1 billion of the world's population lack access to safe drinking water; 1.7 billion lack modern sanitary services and nearly 2 billion lack electricity. One of the major responsibilities of national governments around the world is to assure that vital infrastructure elements necessary to sustain a modern society and economy — such as transportation, communications, utilities, water and sanitary systems, housing and education — are effectively constructed, maintained and operated.

The Impact of Tourism

Not only will the world's population be increasing, but there will be more affluent people. This increased affluence, combined with the influence of the mass media and telecommunications, has contributed to a booming travel and tourism market that places its own unique demands on the transportation systems of individual countries, regions and the world. Travel and tourism is currently the world's largest and fastest growing industry.

Tourism employs more than 200 million people — or one in every nine workers globally — and currently has a gross output approaching $3.4 trillion. People will be traveling who have never traveled before. In the United States, tourism is the number one source of foreign currency and produces more than $50 billion annually. However, at the same time, there is going to be increased global competition for the tourist dollar — from the Caribbean nations, Europe and Asia.

Transportation is the foundation of travel and tourism. Within the next 25 years it is predicted that the U.S. air traffic control system, airlines and airports will have to accommodate more than 1 billion passengers a year — twice as many as today.

More Reliance on Transportation

World trade is currently on the upswing and imports and exports are 20 percent of the U.S. gross national product. An increasing fraction of these goods is handled in containers. Currently, 10 million containers a year are handled in ports in this country, but by the year 2020 this number will have tripled or even quadrupled.

Notwithstanding the growing recognition that the ever increasing use of the personal passenger car and just-in-time delivery system is leading to gridlock and, in the minds of some, environmental misery, there is no end in sight. There will be increased competition for urban corridors between city dwellers and goods carriers.

Since congestion is here to stay, ways to avoid severe gridlock must be figured out. The era of demand-and-build and addressing urban congestion through new construction is over. Even though the speed of intercity travel can be doubled, intracity travel will only get slower. For example, the introduction of the long-awaited high-speed train service between central Boston and New York will still result in the problem of getting to and from the terminal at each end. While moving faster between cities is more exciting, the real problem is how to move people around once they get there.

The world motor vehicle fleet now exceeds 500 million. Over the next 25 years, it is projected to even double or triple in size. Notwithstanding congestion problems, this increase will lead to more global demand for petroleum and more concern about global warming as well as concern about air pollution. It has been jokingly suggested that Armageddon will occur when one billion new car owners in the developing world all get up one morning and turn on their engines at the same time. There is an urgent need for more efficient and less polluting motor vehicles that are petroleum independent.

Safety Crisis

Worldwide, half a million people die from road accidents each year and over 15 million people suffer injuries. Developing and emerging countries account for about 70 percent of these accidents. As the number of motor vehicles in the developing world increases, by the year 2020 fatalities may reach two million per year, with 40 to 50 million injuries. This safety crisis will provide an outstanding opportunity for the United States to share what it has learned about transportation safety.

At the same time, the United States still has much to do about carnage on its own highways. Particularly difficult and sensitive problems are those associated with the aging driver. The developed world has an aging population — 1 out of 5 licensed drivers in the United States will be 65 and over by the year 2020. As people age their reflexes and ability to negotiate traffic tend to decline, posing difficult questions that society must answer:

- When is one too old to drive?
- How does one get to the store and the doctor when he or she does not have a license and lives in a rural area or an affluent suburb?
- And, when does a truck driver who does not have a pension turn in his or her license?

Adjusting to New Defense Concerns

With the end of the Cold War, the defense strategy in the United States has shifted from global to regional conflict. Current Secretary of Defense William Cohen is working to redefine the military's mission and reassess service roles as the focus is being shifted from the former Soviet threat to regional ones such as those posed by Iraq and North Korea.

The world will remain filled with regional aggressors with non-traditional challenges to U.S. power such as terrorist attacks, use of biological or chemical agents, and sabotage of American computer networks. Emphasis has shifted from delivering weapons of mass destruction to transporting men and materials from U.S. bases to anywhere in the world at a moment's notice — as was the case in Somalia, Haiti and South Korea.

Information Technology

Integrating computer and information technology with transportation — knowing where things are at any moment of time, and bringing about a seamless flow of goods — is critical in an age of intense international competition. In the face of this competition, producers will implement just-in-time distribution methods to avoid the expense of tying up large inventories in warehouses in order to offset disruptions in their parts supply chains.

Much of the technology needed to attack information systems is low-cost and widely available to fanatics, local and foreign terrorists, as well as disgruntled employees. Although transportation and logistic systems are being made more effective and efficient through the use of computer and communication technology, they are becoming at the same time more vulnerable to disruption. Safeguards must be built in at the start.

The findings of a recent U.S. Senate investigation on security in cyberspace were chilling. There were more than 250,000 attacks on Department of Defense computers in 1996, and 65 percent were successful. Little is known about who launched them, why or what they found. In one of the few known attacks, a 16-year-old from Britain used a cheap computer in 1994 to hack into the computer at Griffis Air Force Base in Rome, New York. He also gained access to other Air Force systems, and it took them months to recover. In a recent test, Defense Department "red teams" intentionally hacked into 18,200 systems. Only 5 percent of the attacks were detected, and only 27 percent of those were reported.

Early in 1997 a mock cyberwar exercise was conducted at which attendees were asked to pretend they were responsible for briefing the President in response to the following scenario:

- The traffic lights in Manhattan have all turned green;
- The Holland and Lincoln tunnels are shut down;
- Two commercial airplanes have been put on a collision course; and,
- The pressure in the gas lines in the Bronx had been surged, causing all the pilot lights to go out, with numerous fires and explosions occurring as people try to figure out what is going on.

Attendees were asked to determine what the President should tell the nation. One response was simple: "Remain calm and God bless the United States of America." To be honest, no one knew what the President should do. Although much is known how to respond to physical threats to the transportation infrastructure through experience with earthquakes, floods and other natural disasters, the cyberwar threat is very real, very scary and no preparations have been made to respond to the threat.

No Silver Bullets

Looking ahead to the year 2020, the major advances in transportation are not going to be made in mechanical and electrical engineering technologies, but rather as a result of the ongoing revolution in computer and communications technology. Electronic technology — in the form of sensors, computers and communication links — is and will be used to make the most of existing capacity.

There have been periods in the past when the introduction of a "silver bullet" — for example, new electro-mechanical systems such as steam, internal combustion and jet engines — was followed by revolutionary advances in transportation technology. These times — and the conceivable future — do not fall into one of those periods. While there will always be a recurring interest in monorails and levitated vehicles, the major advances in the future will be made through the utilization of information technology to more effectively manage the flow of passengers and goods.

In the developed world, the problems in 2020 will not be solved by building more systems. Instead, they will be solved only by determining how best to use existing transportation capacity more effectively. That is not to say that there will be no new transportation infrastructure construction. The major megaprojects, however, will be in the developing world. For example, the Chinese and other Asian governments are contemplating at least a trillion dollar investment in new infrastructure, including 22 new state-of-the-art airports.

Increased public involvement in transportation issues has lengthened long-term planning horizons. Gone are the days when the New Jersey Turnpike could be built in just two years through the most industrialized stretch of land in the country. Today, the necessary land is no longer available, and people are increasingly reluctant to give up their neighborhoods and homes.

Always look out for unintended consequences. The rapid introduction of the car phone has led to higher accident rates. Deregulation has led to transportation carrier consolidation rather than proliferation. Thirty years ago there were nearly 70 first-class railroads; soon there may be only four.

Some lessons have been learned regarding the waves of change and their possible impact on the global transportation network. Today's engineers and tomorrow's transportation professionals must be prepared to solve the problems of a much more complex world than what existed 25 years ago. Younger engineers, and even those who have been around since ushering in the "modern" age, must be able to integrate social, economic and institutional as well as technical factors into their responses to future transportation challenges since the only thing that is certain is that change will be continuing and unexpected. It is up to the transportation engineer to make that journey of change a pleasant one.

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Digital Shorelines for Boston Harbor

Automatic methods, with some manual intervention, convert images into digital maps more rapidly and portray complex features more accurately than previous methods.

FRANK T. MANHEIM & ANDREW MCINTIRE

Computerized digital mapping of coastal waterways and their environmental conditions requires data files that define the coast and provide a frame of reference for other data being mapped. One way to improve the resolution of available digital shoreline data is by unifying data from the most recent National Oceanic and Atmospheric National Ocean Survey (NOAA/NOS) charts.

Shoreline files are in vector format — *i.e.*, they are in the form of sets of data points that define connected line segments. Compiling them might seem a relatively simple and straightforward matter, but the increasing need for digital shoreline data has pointed up variables and problems in their acquisition and use. For example, the definition of the shoreline as the boundary between land and sea poses special problems:

- Which tidal stage is chosen, and with what corrections?
- Should high-water, mean sea level or low-water based datums be used?

The latter will encompass features like sand bars and mudflats that are only intermittently exposed.

In addition, geographical information systems (GIS) and some gridding and mapping systems require completed shoreline "polygons" — *i.e.*, the shoreline must form a closed loop, which lead to another set of problems:

- In the case of streams and canals, how far upstream should artificial closures be drawn?
- How many man-made constructions (like bridges, docks and jetties) should be shown?
- What resolution is needed for given purposes (neither too small nor too great)?

Improved Resolution

Current coastal engineering demands greater resolution (accuracy) for shoreline projects. For example, projects in Boston — including the Central Artery/Tunnel Project — require both the highest resolution possible as well as the ability to easily use the information in digital

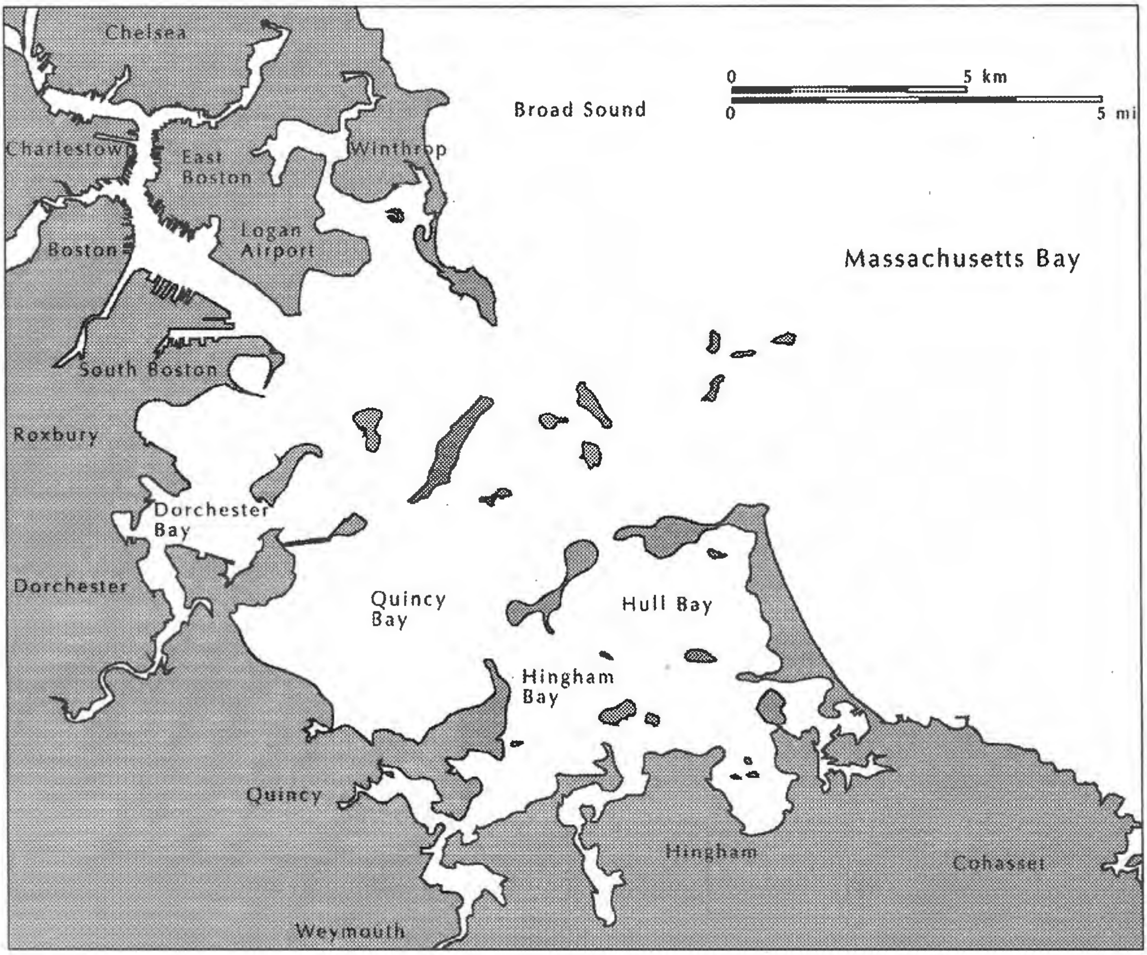

FIGURE 1. Location map for Boston Harbor, modified from the NOAA Massachusetts Bay Nautical Chart.

form. New and existing shoreline data for the greater Boston Harbor area (see Figure 1) have been compiled into a new shoreline file by digitizing and combining the most recent charts. Up-to-date digital shoreline files are required to support coastal GIS displays that combine data from multiple sources. The new Boston Harbor data set can then be compared with earlier shoreline data sets — such as the Massachusetts Coastline (MCOAST) compiled by MassGIS from U.S. Geologic Survey (USGS) digital line graphs (DLGs) with supplementary digitization from USGS topographic maps; NOAA's Medium Resolution Digital Vector Shoreline (NMRDVS); and recent, high-resolution orthophotographic coverage — to reveal changes due to coastal construction as well as discrepancies that need resolution.

NOAA/NOS hydrographic charts of Boston Harbor were used (NOAA/NOS charts #13270 and #12272) to create the new shoreline file.[1,2] The new shoreline data set — hereafter referred to as BHS (Boston Harbor Shoreline) — combines those two charts, the most recent and detailed nautical charts available. These charts are both dated 1996 and have scales of 1:25,000 and 1:10,000 (Inner Harbor), respectively. As is often the case, the chart dates refer to the date of the navigational information. However, the shoreline data are probably older but their actual dates are not stated on the charts.

One other application of computerized digital mapping is to aid in the study of chemical contaminants in bottom sediments and contaminant transport in Boston Harbor and adjoining parts of Massachusetts Bay. Active re-

TABLE 1.
Representative Autodigitization/Autovectorization Software Products

Software Product	Notes/Features	Manufacturer
ABICAS	Free-standing system	ITA
ArcScan	Works within ArcInfo system	ESRI
AutoCAD Map	Works within AutoCAD system	AutoDesk
Autotrace	Part of MapInfo GIS system	MapInfo
Infotec, LT4X	Free-standing system	Pace
MapFlex 2000	Free-standing system	Audre
Vectorizer	Part of Microstation GIS system	Integraph
Vtrak	UNIX-based black & white or color system	Laserscan

search in this field is facilitated by digital mapping.[3-5]

Shoreline Definitions & Issues

Shorelines in the United States are a federal responsibility, which for domestic purposes is handled by NOAA/NOS and its contractors.[6] The terms *coastline* and *shoreline* are considered synonymous according to a leading treatise on coastal mapping.[7] Both terms are defined as the line of contact between land and selected water elevations. The term *coastline* occurs in several recent Congressional acts, such as the Coastal Zone Management Act. Most commonly it is often used to signify the permanent high water boundary. For more generalized quantitative measures, *coast* or *coastal zone* tend to be employed, whereas *shoreline* refers to more detailed delineation. *Baseline* is a term used in international law to indicate the reference line from which the marginal sea and other offshore zones are measured. The official U.S. baseline is the mean low water (MLW) line along the coast, which includes tidal flats.

For tidal waters the shoreline is normally mean high water (MHW). For non-tidal waters it is normally the mean water level. MHW and MLW refer to the average high and low tidal levels for a 19-year period, not necessarily the most recent one. Mean lower low water (MLLW) level refers to the lower of the two daily tidal levels in those areas where diurnal tides dominate. A corresponding definition applies to mean higher high water (MHHW). A 1980 international convention has stipulated that *lower low water level* be used as the standard for all soundings on nautical charts, since it provides the lowest water levels likely to be encountered in navigation. (Data on the lower low water level are included in the NOAA/NOS Boston Harbor charts.)

Shoreline data are used for legal, administrative, regulatory/cadastral, as well as state and federal sovereignty purposes (such as determining federal-state boundaries). In addition, they are used to aid maritime navigation (as in nautical charts and bathymetric maps), and to facilitate the assessment of coastal flood zones, erosion and subsidence. They are also needed for military concerns, as well as for the engineering and construction of coastal structures.

Technical aspects that require consideration while preparing shoreline data for digitization include:

- Topological "closing lines";
- Geodetic control reference standards;
- Georectification of orthophoto and satellite imagery;
- Metadata (documentation of the quality, source and other information on the data used);
- Certification and validation; and,
- Attributes.

Attributes refer to the nature or characteristics of shoreline features (such as rocky, sandy and

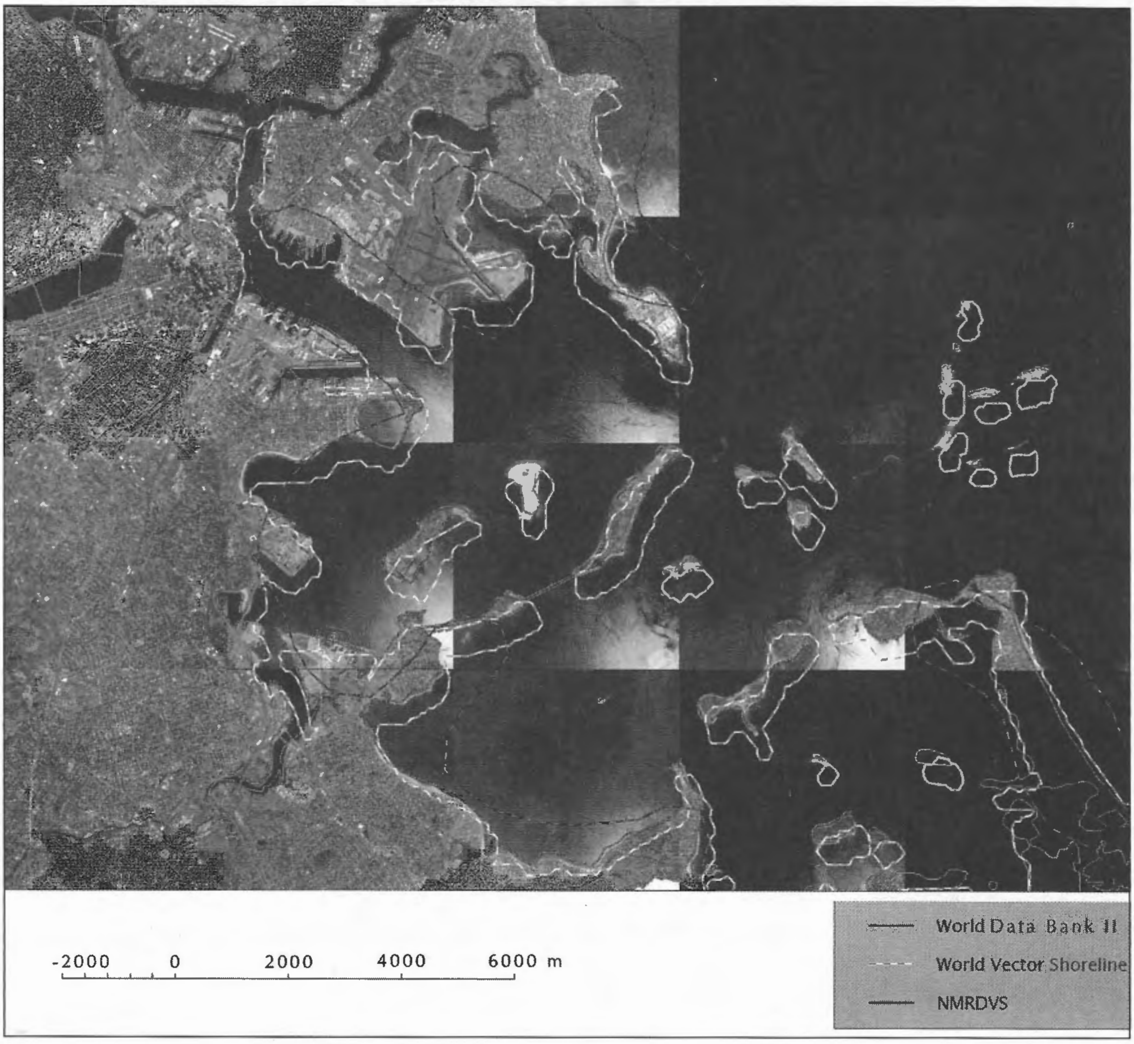

FIGURE 2. Low to medium-resolution shoreline data plotted for Boston Harbor.

muddy). Horizontal accuracy is referenced to the National Map Accuracy Standard.[8] The vertical standard is referenced to tidal data measured by NOAA/NOS. Numerous sources present discussions of the accuracy of elevation contours and datum references.[7,9-13]

Digitization Methods

A traditional, and still common, method of preparing digital files is by using a digitizing tablet with a "hockey puck" digitizer to encode data points. The source map, or *orthophoto*, is registered geographically, and the data points can then be defined relative to this system. Manual digitization is slow and is being widely supplanted by autodigitization and vectorization techniques. A number of software programs running on a range of computer platforms is available today for automatic vectorization. Table 1 (on page 37) presents some of the more common software automatic digitization and/or vectorization programs. These progams are commonly referred to as raster-to-vector conversion systems, or intelligent document conversion systems.

The software system chosen to perform the work on the Boston Harbor charts utilized an autovectorization system that operated on scanned and projected raster images. If the source material was in multiple parts (for example, adjacent aerial photographs or maps that were too large to be scanned in one piece),

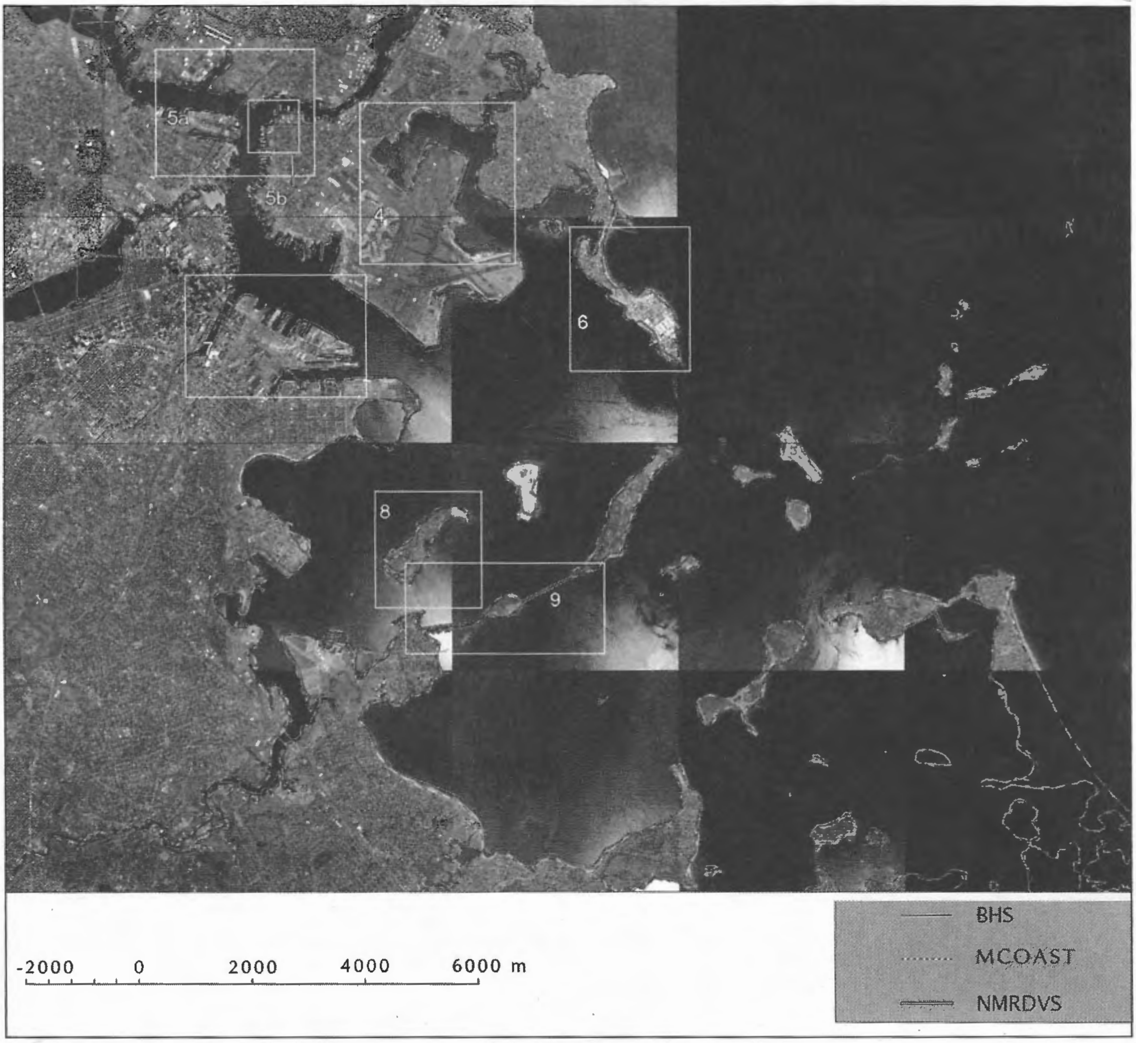

FIGURE 3. Medium to high-resolution shoreline data plotted for Boston Harbor

images were scanned in sections, georeferenced by use of locations at corners and then tiled together. All processing was performed on desktop computers.

The scanned images were saved as 24-bit Targa files and then converted to the vectorizing software's proprietary file format. The images were processed to reduce the amount of dithering and the pixilation of colors. The user then selected a color to follow and clicked two points on a line of that color. If the option to use a completely automatic trace method was chosen, the software followed the line until it came to a dead end or the edge of the screen, at which point the user could accept or reject the line. If the option to use a semi-automatic trace method was chosen, the software would prompt the user to accept or reject each point as it was added. The semi-automatic method could be quite useful if the line being digitized crosses other lines of the same color or had many tight bends. When using semi-automatic mode, the user could interrupt the tracing to add points manually (for example, to take a coastline past a bridge or to close off a river mouth in a coastline).

The orthophotos used as the background for comparing shoreline files had a ground resolution of 0.5 by 0.5 meter, obtained from aerial photography at a negative-equivalent scale of 1:30,000. The image files were downloaded from their source at the Massachusetts Institute

FIGURE 4. The northern part of Logan Airport and adjacent waterways. Shoreline delineation is strongly affected by tidal levels in the very shallow waters and marshes in the northwest sector but, with few exceptions, the agreement is good.

of Technology (the MassGIS web site). The orthophoto images were resampled to reduce the number of pixels by a factor of 4, which resulted in a file with a ground resolution of 2.0

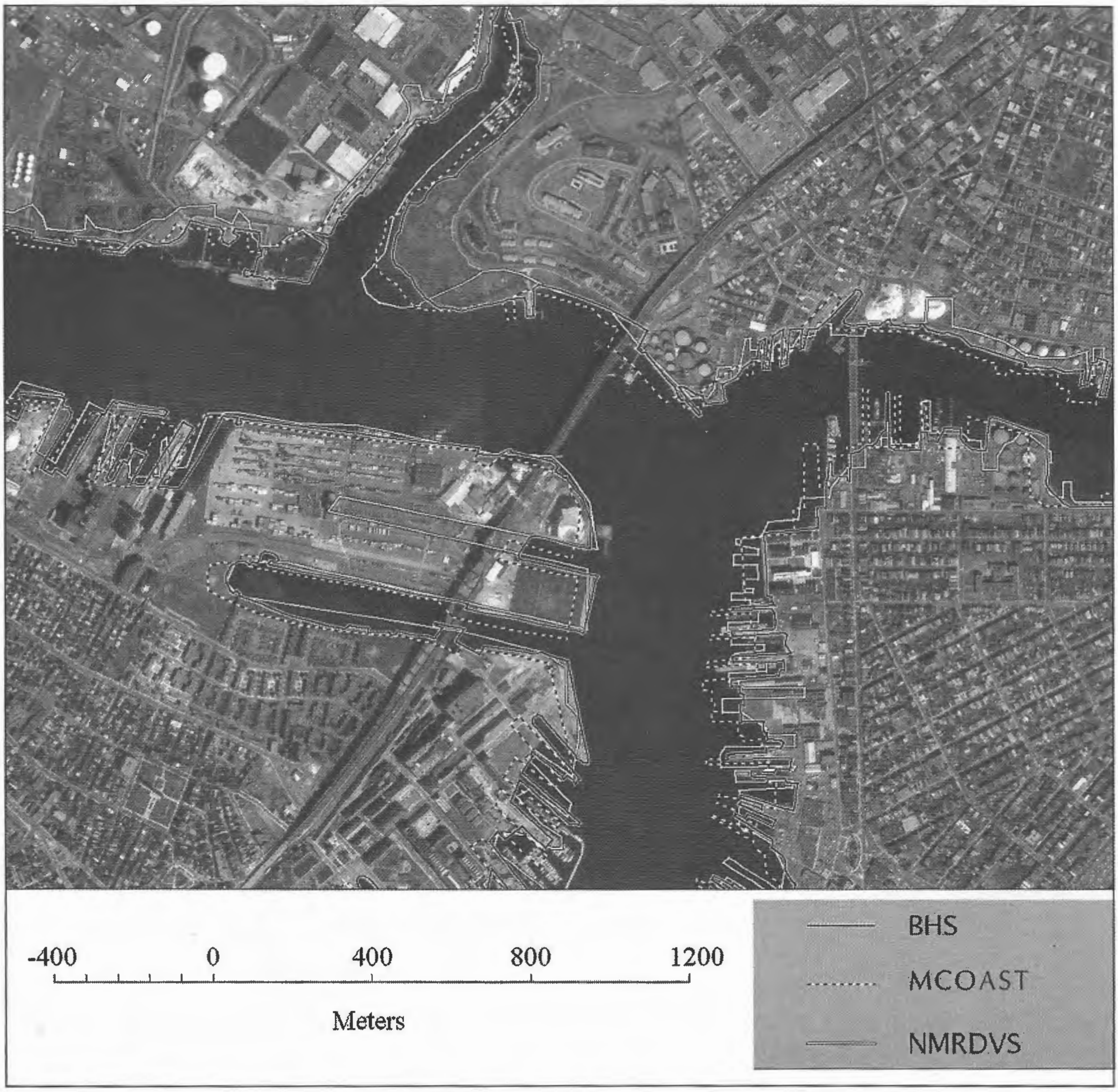

FIGURE 5A. The confluence of the Inner Harbor with the Chelsea and Mystic Rivers. This figure has the same scale as Figures 4, 6, 7, 8 and 9. Greater resolution for the complex, man-made shorelines in the inner harbor area is provided by Figure 5b.

by 2.0 meters. The images had been rectified to Massachusetts State Plane, North American Datum (NAD83). To tile the images together, the state plane coordinates were first converted to decimal latitudes and longitudes. This conversion was accomplished using software released by the U.S. Army Corps of Engineers.[14] All sources of information (except MCOAST) were based on NAD83. The original topographic map data upon which the USGS DLG data are based were derived from 1978 overflights.

Shoreline Comparison

A selection of existing low- and medium-resolution shoreline files is displayed in Figure 2 (on page 38). Scales for the files are 1:2,000,000 for World Data Bank II, 1:250,000 for World Vector Shoreline (Defense Mapping Agency) and 1:80,000 for NMRDVS. Medium- and high-resolution shoreline files are shown in Figure 3 (on page 39). Scales for the files are 1:80,000 for NMRDVS, 1:24,000 for MCOAST, and 1:25,000 and 1:10,000 for BHS. Data from NMRDVS are

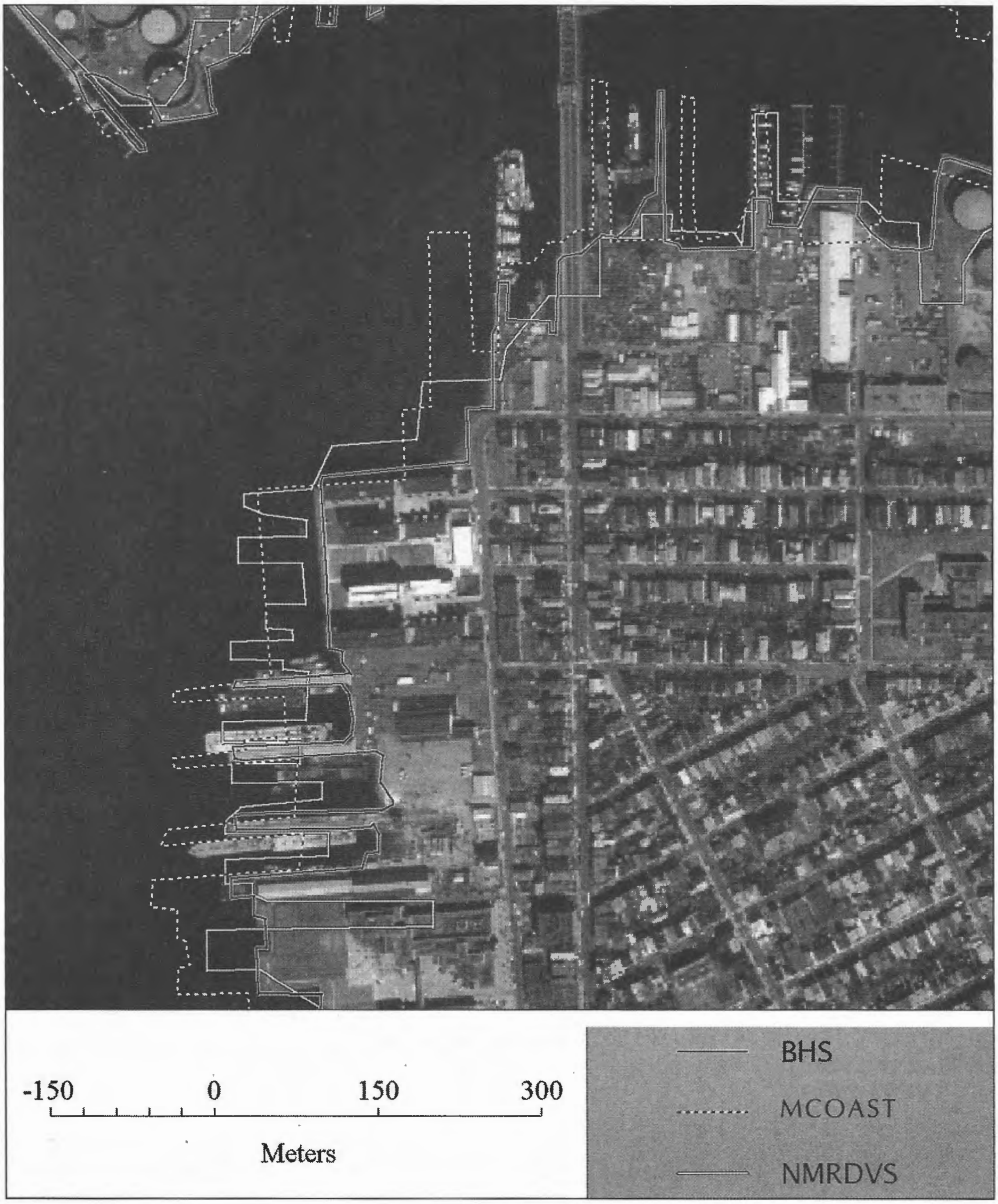

FIGURE 5B. The confluence of the Inner Harbor with the Chelsea and Mystic Rivers (an enlargement of the subarea shown in Figure 5a). The 1:80,000 resolution of the NMRDVS is not sufficient or probably intended to resolve the complex features. A higher resolution is needed to depict the shore for engineering development, or for the location of sediment samplings for dredging or environmental purposes.

common to both. Whereas the NOAA shoreline has a variable scale (with an average scale for the entire NMRDVS of approximately 1:70,000), the chart used for Boston Harbor

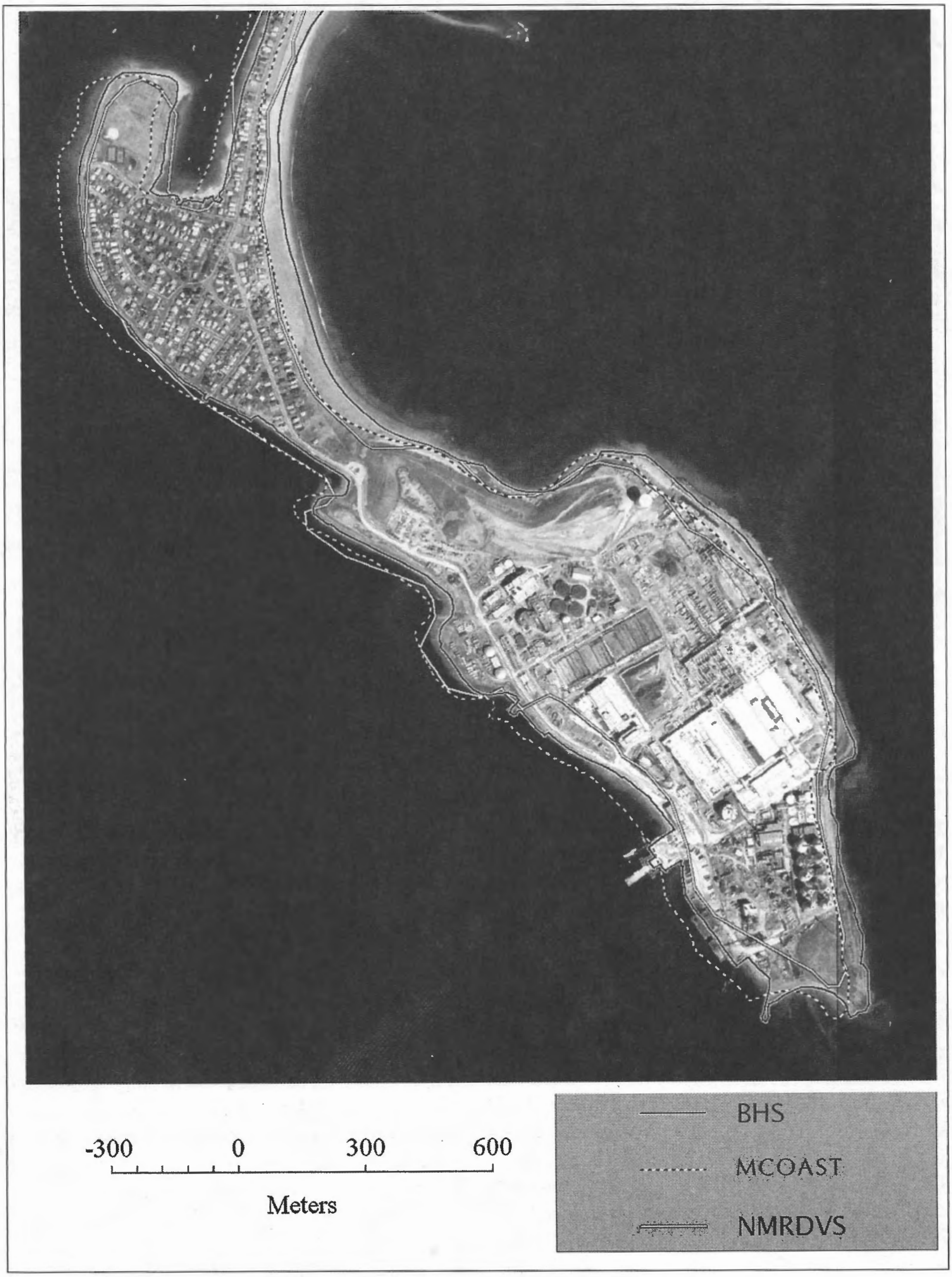

FIGURE 6. Up to 100-meter departures between the NMRDVS and BHS shorelines can be observed on the eastern and southwestern shores of Deer Island. The NMRDVS shows a prominent inland offset in the northeastern part of the peninsula.

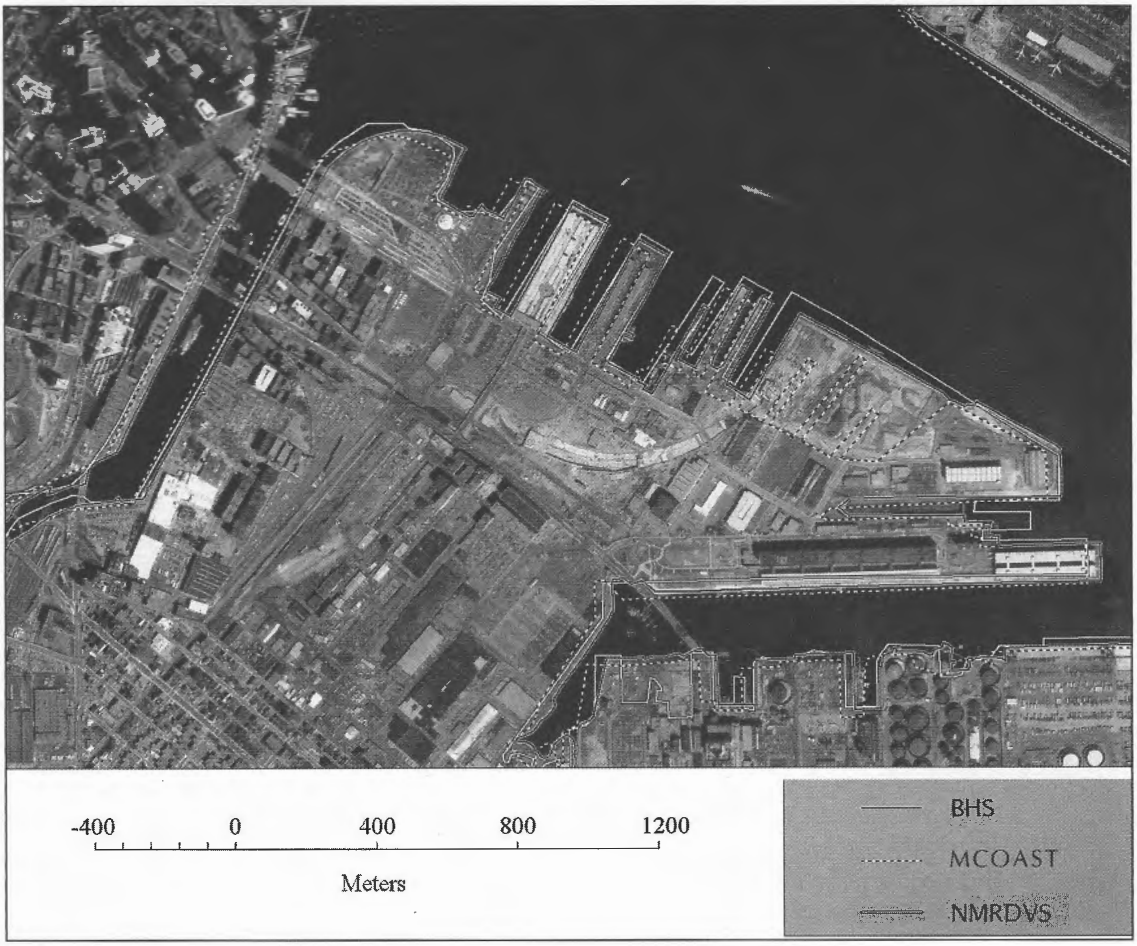

FIGURE 7. The MCOAST shoreline clearly shows older harbor areas in the eastern segment of the Inner Harbor north of the Reserved Channel. Their filling in is reflected in the newer shorelines. Except for a difference in the southwestern margin of the Reserved Channel, the other two shorelines agree quite closely.

(#13267) is 1:80,000. On a page-sized diagram of Boston Harbor as a whole, the differences between the three latter files are not great. Agreement is good in many of the outer and middle-harbor areas. However, comparisons between the shoreline files and recent orthophotos show significant local differences particularly in the Inner Harbor and the Mystic River confluence. In these areas the NMRDVS lacks sufficient detail to effectively delineate the shoreline at high resolution.

Figures 2 and 3 display shoreline files superimposed on a mosaic created from a set of orthophotos based on recent aerial photographic coverage of the greater Boston area.[15] The differences between NMRDVS (1:80,000 scale), the MCOAST (1:24,000 scale), and the new BHS file (1:25,000 and 1:10,000 scale) emerge at larger scale, as depicted in Figures 4 through 9. MCOAST is an earlier high-resolution shoreline file and there is often a systematic deviation between MCOAST and the other lines. Some differences are clearly due to changes in the harbor since the data in the original topographic maps were compiled. Others may originate in differing tidal levels, or in processing. Figure 3 also shows the locations of Figures 4 through 9 within the Boston Harbor area.

In general, all three files — BHS, MCOAST and NMRDVS — tend to show a systematic westward offset with a mean of about 30 meters from the orthophotos for both the Outer

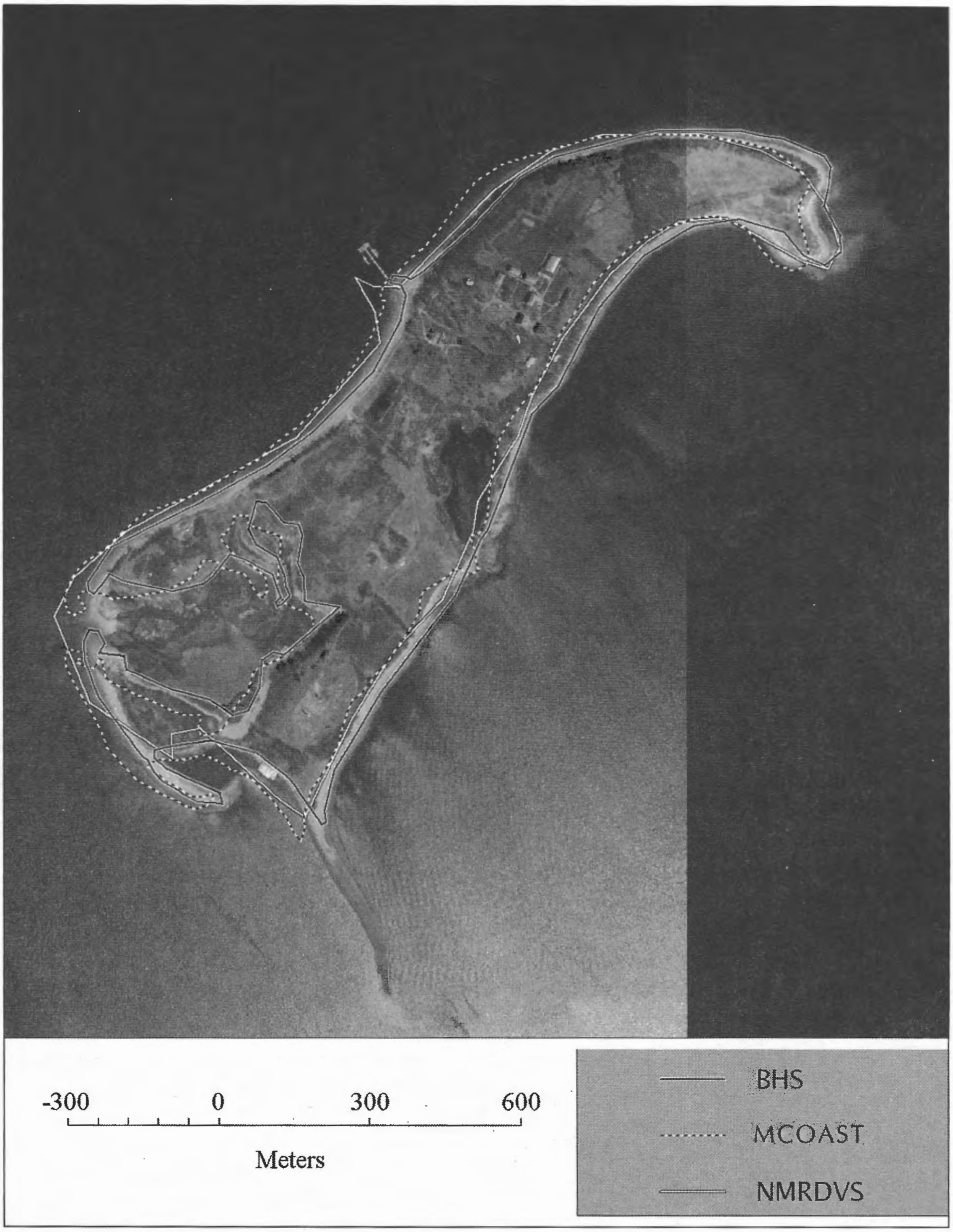

FIGURE 8. Thompson Island. The southwestern margin demonstrates a closed contour in the NMRDVS, whereas the BHS shows an embayment.

Harbor and Inner Harbor areas. The source or sources of this systematic offset could not be identified at this time. It is suggested that this offset be considered and resolved in future

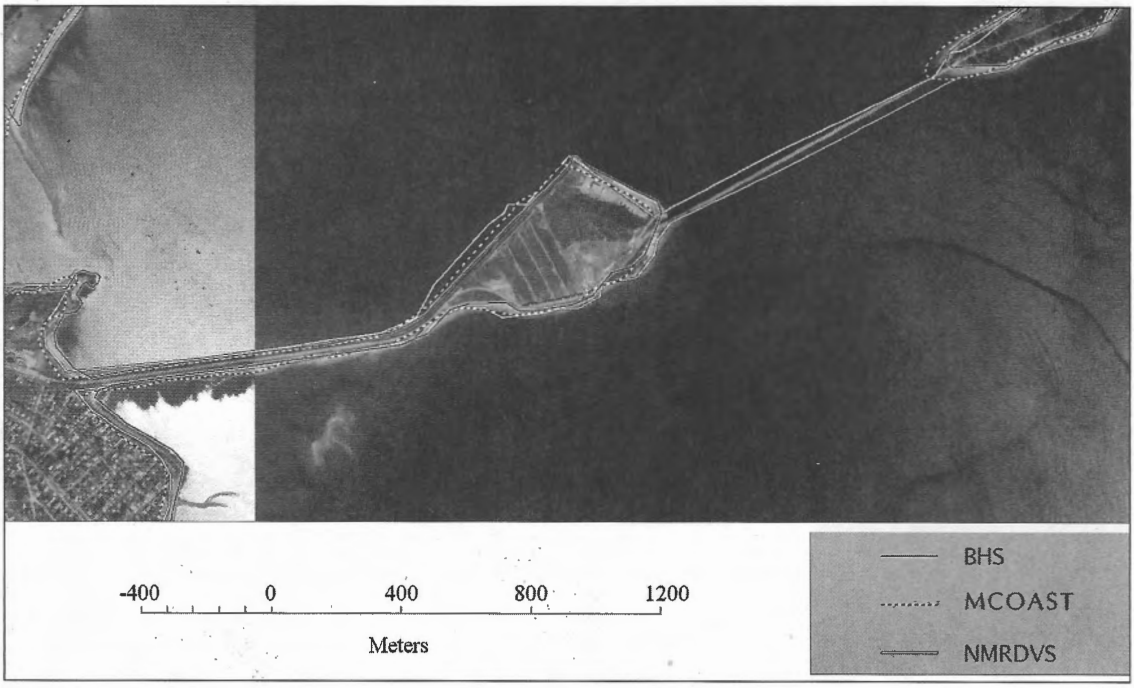

FIGURE 9. Moon Head and Squantum Head. The causeway between the two islands, to the west, is shown as land on all the shorelines, whereas the bridge between Moon Island and the larger Long Island (eastern sector) is shown as water in the MCOAST shoreline.

map additions or GIS treatments of Boston Harbor.

In Figures 2 and 3 and the enlarged insets there can be seen shadowy reflections from the water itself. In some areas, such as near the shore of Hingham Bay, these "reflections" may outline shallow mudflat areas, but elsewhere they may be due to surface reflections of various origins.

Data Sources

The following items include the data sources used in this study as well as some others that are included for completeness:

- *Massachusetts Institute Technology & MassGIS Digital Orthophoto Project.* Jointly sponsored by the Planning Support Systems Group, Department of Urban Studies and Planning, Massachusetts Institute of Technology, and MassGIS. Its web site, entitled "Tools to Facilitate Access to Digital Orthophotos," is a node on the National GeoSpatial Data Clearinghouse. Web site: ortho.mit.edu/nsdi/.
- *Massachusetts Geographic Information System (MassGIS).* Part of the Commonwealth of Massachusetts Executive Office of Environmental Affairs. Its web site has no data online, but has product descriptions and order data. MassGIS developed MCOAST, a complete Massachusetts shoreline file originally created combining data from USGS 1:24,000 scale DLGs and digitized shorelines of topographic maps where DLGs were not available. The original topography is mainly based on aerial photography taken in 1978. Web site: www.magnet.state.ma.us/mgis/massgis. htm.
- *NOAA Medium Resolution Digital Vector Shoreline (NMRDVS).* The NOAA/National Geophysical Data Center web site is: www.ngdc.noaa.gov/mgg/shorelines/.
- *NOAA Office of Ocean Resources Conservation & Assessment (ORCA).*
- *Digital coastline segments* (digital t-sheets and documentation) are available from this web site: seaserver.nos.noaa.gov/projects/shoreline/shoreline.html.

- *U.S. Army Corps of Engineers, Topographic Engineering Division.* Software for converting coordinates to and from geographic, state plane and universal transverse mercator projections is available for downloading from: ftp://survey1.tec.army.mil/pub/software/corpscon.410/v41xzip.
- *USGS Coastline Extractor.* The 1:2,000,000 scale World Data Bank II/CIA global and 1:250,000 scale World Vector Shoreline global data sets also include the NMRDVS (1:70,000 scale) data set, as well as a link to the primary NOAA web site. Web site: crusty.er.usgs.gov/coast/getcoast.html.
- *USGS Boston Harbor Ecosystems.* This source includes figures from this article and BHS digital files in downloadable format. Web site: coast-enviro.er.usgs.gov/boseco/.
- *USGS/National Mapping Division (NMD).* This source provides DLGs and other map information. Other scales available range from 1:10,000 to 1:1,000,000 from USGS quadrangle maps. Web site: edcwww.cr.usgs. gov/glis/glis.html.

Conclusions

There are a number of benefits to using newer automated digitization methods:

- A new digital shoreline file for Boston Harbor has unified the two existing harbor charts (NOAA/NOS charts #13270 and #12272).
- Digitization by the newer autovectorization techniques can be completed more rapidly and also more accurately than by manual digitization techniques. The scanning and processing can be applied to a map of any size and performed on desktop computers. Manual intervention is needed to take into account shoreline indentations like rivers and canals and may be needed for complex inner-harbor features.
- Comparison of the new digital file with existing digital files shows that the new file is distinctly superior to the standard 1:80,000-scale file in the more complex Inner Harbor areas. Systematic shifts in the harbor maps of up to 30 meters, and local shifts (for example, at Deer Island) as great as 100 meters in comparison with recent orthophoto coverage should be resolved in preparing future harbor charts.

NOTES — *The new data set presented here represents the most detailed delineation currently available. It may be downloaded from the web site: coast-enviro.er.usgs.gov/boseco/. The ABICAS software system was used for vectorization in this study. CorpsCon software, available from the U.S. Army Corps of Engineers, was used to convert coordinates to and from geographic, state plane and universal transverse mercator projections. Reference to any specific commercial product, or trade name does not imply its endorsement by the U.S. Geological Survey or the Boston Society of Civil Engineers Section/ASCE.*

ACKNOWLEDGMENTS — *Millington Lockwood, at the National Oceanic and Atmospheric Administration/National Ocean Survey (NOAA/NOS), gave permission to use a briefing report, and provided valuable supplementary information. Christian Jacqz, at the Data Center for the Executive Office of Environmental Affairs (MassGIS), transferred to the authors the Massachusetts digital shoreline derived from USGS topographic maps, and provided information on the recent cooperative orthophoto coverage of Boston Harbor. Norman Vine, of Woods Hole, Mass., cooperated in the earlier data transfers.*

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15. The Planning Support Systems Group at the Massachusetts Institute of Technology (MIT) Department of Urban Studies and Planning, the MIT Department of Urban Studies and Planning, and MassGIS supply tools to facilitate access to digital orthophotos. Web site: ortho.mit.edu/.

Partnering & Its Implementation on the Central Artery/Tunnel Project

Partnering can foster better communication among project participants as well as have many beneficial effects on contract cost change and schedule change.

MICHELLE GILLELAND DAIGLE
& ALI TOURAN

Partnering is an alternative form of conducting business in which two or more organizations make long-term commitments to achieve mutual goals by entering into an agreement that requires a team-approach to the job. It creates an environment that is conducive to reducing costs and litigation, and increasing quality and productivity.[1] Partnering is a relationship in which:

- Trust and communication are encouraged and expected from all participants.
- All parties seek solutions to problems that are agreeable and meet the needs of everyone involved (a *win-win approach*).
- All parties have identified common goals for the partnership and, at the same time, are aware of, and respect, each other's goals and values.
- Partners seek input from each other in an effort to find better solutions to the problems and issues at hand, creating a *synergy* in the relationship that fosters cooperation and improves the productivity of the partnership.

The Construction Industry Institute (CII) defines partnering as:[2]

> A long-term commitment between two or more organizations for the purpose of achieving specific business objectives by maximizing the effectiveness of each participant's resources. This requires changing traditional relationships to a shared culture without regard to organizational boundaries. This relationship is based upon trust, dedication to common goals, and an under-

TABLE 1.
Summary of the Results of Partnered Versus Non-Partnered Projects in Three Studies

Studies & Performance Criteria	Partnered	Non-Partnered	Improvement (%)
U.S. Army Corps of Engineers, all districts (Ref. 6)			
Number of projects considered	16	28	
Cost change (%)	2.72	8.75	69
Schedule change (%)	9.07	15.53	42
Change orders (%)	3.87	7.74	50
Claims cost (%)	0.67	5.01	87
VECP* (%)	0.73	0.05	1,360
U.S. Naval Facilities Command (Ref. 7)			
Number of projects considered	39	100	
Cost change (%)	11.20	9.79	-14.4
Schedule change (%)	13.54	25.93	47.8
Change orders (%)	11.34	9.38	-20.9
Claims cost (%)	0.04	0.57	93
VECP* (%)	0.17	0.01	1,600
U.S. Army Corps of Engineers, Kansas City District (Ref. 8)			
Number of projects considered	10	13	
Cost change (%)	3.98	6.45	39
Schedule change (%)	14.71	33.00	56

* **Note:** VECP = Value engineering change proposal

standing of each other's individual expectations and values. Expected benefits include improved efficiency and cost effectiveness, increased opportunity for innovation, and the continuous improvement of quality products and services.

History of Partnering

The use of partnering in the construction industry has grown significantly in recent years in both private and public sectors. Its growth is similar to the increasing use of alternative dispute resolution (ADR). Owners and contractors are using partnering in an attempt to eliminate adversarial positions, reduce disputes and litigation, improve schedules, reduce costs, and generally improve project performance. Even though partnering originated in the United States, its use has crossed national borders and several examples of partnering on international projects are available. As an example, *New Civil Engineer*, published by the United Kingdom's Institution of Civil Engineers, ran a special section on partnering in its April 10, 1997 issue.[3] It featured several success stories on the use of partnering on large-scale projects in the United Kingdom.

In the United States, the use of partnering, in its present form in private sector construction, started in the mid-1980s. A large chemical manufacturer was the first organization to use partnering in large-scale construction with a contractor to build numerous facilities.[4] The U.S. Army Corps of Engineers (COE), Mobile, Alabama District, was the first public agency to use partnering in its construction projects. In 1988, the COE decided to use partnering in an $80 million project with a duration of approximately four years. The COE proposed the idea to the contractor, which agreed to try this new approach to conducting business. The process used to develop that partnership formed the framework by which many public sector partnerships are formed today.[5]

Partnering on Past Projects

An extensive literature search was conducted to collect information on projects where partnering was used. Table 1 provides a summary of the findings from three studies. Each study contained qualitative and quantitative analyses. The qualitative analysis was achieved mainly by interviewing the owner's representatives. The relatively large number of projects analyzed permitted statistical analysis of data including tests of hypotheses. In all these comparisons, a number of projects using partnering were compared with a number of projects that did not use partnering. The assumption was that the comparison could provide at least a broad assessment of the impact of using partnering in construction projects. While this assumption is valid for general evaluation, it disregards many parameters that may impact project performance criteria — such as project type, size and specific contractual requirements.

The first study presented in Table 1 analyzed a number of COE projects covering all districts.[6] The second study looked at a large number of projects executed by the Naval Facilities Engineering Command (NAVFAC).[7] The third study examined numerous projects executed by COE's Kansas City District.[8]

The criteria used to measure project performance were similar in all of these studies and other studies that were reviewed. In each case, the objective was to evaluate the impact of partnering on cost and schedule growth and its ability to foster an environment that was conducive to productive cooperation between the parties involved. In all the studies that were reviewed, the partnered projects substantially outperformed the non-partnered projects in the categories of cost growth, schedule growth, change order volume, claims cost and value engineering savings. The only exception was in the NAVFAC study.[7] That study reported a better average performance in areas of cost and change growth for non-partnered projects. Despite better performance in those areas, schedule performance was much better in the partnered projects. Furthermore, the authors of that study interviewed more than 200 NAVFAC engineers and personnel with regard to their perceptions of the partnering process. The interview results were generally very positive and indicated that partnering helped to avoid claims, increased value engineering proposals and savings, and opened communication for resolving tough construction problems. The negative comments were that owners tended to pay the contractor off rather than standing firm on claims, and owners' accessibility at partnering sessions helped create more changes.

Several other sources have reported on the performance of partnered projects in recent years. Most of these studies have presented a positive overview of partnering and have attested to the fact that using this approach helped improve communication between parties and significantly reduced claims and litigation.[9,10]

All the studies reviewed involved public projects. It is possible that private owners are less inclined to publish cost and schedule data for their projects, or perhaps private projects are using partnering less than the public sector (which may be the case since public and private sector projects are quite different in many ways). For example, public projects tend to be awarded to the lowest responsible bidder and involve numerous political considerations. Private projects may use restricted bidder lists, negotiated contracts and alternate delivery methods (such as design-build or cost-plus), which may make private sector contracts less adversarial and less in need of partnering.

The Partnering Process at the Central Artery/Tunnel Project

The Central Artery/Tunnel (CA/T) Project is the largest public works project currently underway in the United States. The project, with an estimated budget of $7.78 billion (1994 dollars) plus inflation, consists of constructing and replacing 7.5 miles of highway in the downtown area of Boston. The project is managed by a joint venture of a construction management firm and an engineering firm for the Massachusetts Highway Department (MHD). Major funding comes from the Federal Highway Administration (FHWA), which is actively involved in overseeing project design and construction. Supplemental funding comes from the Commonwealth of Massachusetts. Much information is available about various aspects of the project. One source, for example, is the special focus issue of *Civil Engineering Practice* on the CA/T Project published by the Boston Society of Civil Engineers Section/ASCE.[11]

The CA/T Project started implementing partnering in 1992. The motive for adopting partnering was to use it to find ways to meet tight schedules, keep costs down and minimize litigation. The project requests partnering on all construction contracts with a duration of at least one year and a bid value of more than $1 million. In 1995, the project also decided to implement partnering on large design contracts that had not yet been awarded. Although design contracts are usually less adversarial, the CA/T Project recognized that these contracts could benefit from the improved communications, team approach and issue resolution techniques offered by partnering. In both construction and design, participation in partnering is voluntary and encouraged. The direct expense costs of partnering are shared 50-50 between the project and the contractor or design consultant.

The MHD is an active participant in the process and has created within its Construction Department a Partnering Department that coordinates and implements the partnering process for the entire CA/T Project. The Partnering Department is responsible for, among other things, identifying projects that should be partnered, advising contractors and designers, coordinating partnering workshops, facilitating partnering follow-up meetings and steering committees, and monitoring and evaluating the progress of partnering relationships. A dedicated partnering department has been key to keeping the partnering program on track at the CA/T Project. The large number of contracts, and their complexity, requires strong coordination and extensive planning and follow-up. Many state departments of transportation or highway departments have staff dedicated to managing their partnering programs.

Leadership Training Course. The first step in the partnering process is to send key personnel to a leadership training course prior to their participation in the partnering workshop. Success in partnering depends to a great extent on the attitudes and behavior of the people involved and their ability to work in teams. Leadership training can prepare key personnel for the requirements of an effective partnering venture by emphasizing the principles that the project leadership believes are essential for an effective partnership.

There are several leadership training courses available providing a wide range of services. The CA/T Project selected a course based on Stephen Covey's book, *The Seven Habits of Highly Effective People.*[12] The seven habits as taught by Covey are:

1. *Be Proactive.* The behavior of human beings should be a function of their decisions and not their conditions. People have the initiative and responsibility to make things happen.

2. *Begin With the End in Mind.* Identify your own goals and core values clearly so that your actions will always take you toward your goals in accordance with your values.

3. *Put First Things First.* Focus on important activities to preserve and improve relationships and accomplish results. These activities are important but not urgent and include long-range planning, preparation and preventive maintenance. Putting first things first minimizes the number of activities that become urgent because it focuses on preparation and preventive activities rather than crisis resolution.

4. *Think Win-Win.* Develop solutions or make agreements that are mutually beneficial and satisfying to all parties. This philosophy embodies the spirit of teamwork. If all parties are happy with the solutions, they will be committed to the action plan.

5. *Seek First to Understand, Then to Be Understood.* Listen with empathy and understand the other person's concerns from his or her point of view first, before speaking and expressing one's own views.

6. *Synergize.* Strive hard to tap the different strengths and knowledge of each of the team members to create new solutions that are better than those any one person could have come up with on his or her own.

7. *Sharpen the Saw.* Work continually to preserve and improve yourself physically, mentally, socially and spiritually.

The CA/T Project believes that habits #4, #5 and #6 are the most important for effective partnering. These habits focus on working together in teams, communicating effectively and valuing everybody's input and contribution to develop better solutions to any problems that may arise. In general, these characteristics are not usually natural to many managers and engineers. Instead, most of these professionals have been conditioned through school and on the job to work alone to solve problems. Therefore, formal training in this area can help participants to better prepare for a partnering relationship based on teamwork, trust and communication.

The personnel that are sent to this course include the MHD Project Director, all MHD construction managers and assistant managers, and several other MHD staff. The joint venture team sends all construction Resident Engineers who will be involved with partnered projects and many Assistant Resident Engineers. The joint venture team also sends all Area Construction Managers. Because the use of partnering has expanded to design contracts, most Area Design Managers and all Project Engineers managing a final design contract who will participate in a partnered design contract are sent to the leadership training course. Contractors and design consultants are encouraged to send their Project Managers as well, which they most often do.

Initial Workshop. Once a contract is awarded, the MHD Project Director invites the contractor or the design consultant to form a partnership for the project. After the contractor or the design consultant agrees to participate in partnering, an initial partnering workshop is scheduled, which usually consists of a two-day workshop held at a neutral location such as a hotel. A neutral facilitator hired from outside the partnering firms runs the workshop.

The format for these workshops is rather flexible. However, in a standard workshop the work starts by introducing all participants and allowing them to get to know each other. Often, the facilitator has each participant fill out a survey (such as the Myers-Briggs type indicator — a standard psychological assessment tool) to identify his or her personality type. This assessment is valuable because it shows how teams are comprised of different personalities and strengths, which should be recognized and utilized by the team members when resolving problems.

Participants are then usually separated into their individual organizations and asked to write out goals for their company or organization on the contract. Each group comes back and presents its goals to the other groups. Then, everyone identifies one set of mutual goals for the team, which meet the needs of all members. Stating goals is a valuable exercise because it points out that the different organizations have many of the same goals and objectives. Typically, all parties agree that meeting quality, safety, schedule and budget are important project goals. Some contracts develop specific measurable goals in a "report card" format and periodically evaluate how well the team is meeting these goals. Developing a procedure to regularly assess whether goals are being met is encouraged on all contracts.

Participants at all initial workshops are required to develop a partnering agreement for the team that everybody signs. This agreement states the goals for the team and expectations for the partnership, and commits the individuals to the goals listed. Figure 1 shows a sample agreement.

The next phase in the workshop is to divide the participants into random groups to work on a team-building exercise. This exercise can take various forms but it emphasizes concepts such as win-win and synergy that are vital to partnering success. The exercise teaches members how different organizations on the contract must work together for the mutual benefit of the entire team and the project. Otherwise, one group can benefit at the expense of another.

Most of the workshop's time is spent by having groups formed from personnel from the partnering companies develop action plans for specific contract issues and problems. This process allows people from various organizations to work together in teams to solve problems with solutions that are acceptable to all parties. Often, teams choose to develop action plans to improve communications, to foster decision-making at the lowest levels or to reduce paperwork. During the

South Boston Interchange (West)

Partnering Charter

September 24, 1997

As a team, working in harmonious partnership, we pledge to each other and the community to construct, with quality and pride, the C01A6 project safely, on schedule and within budget while fostering personal growth of all team members. We are committed to open, honest communication; to professionalism, expedient resolution of disputes; to be good neighbors in the community; and to the creation and maintenance of a positive and supportive environment.

Major Goals

- Maintain a safe working environment with a zero-accident philosophy
- Produce a quality project creating a sense of pride for all team members
- Meet budget and schedule requirements as outlined by the contract
- Create a win-win situation for all parties through open communication and timely response to issues
- Issue resolution at the field level
- Timely payment to all parties
- Interactive community relations as well as open dialogue with neighboring contracts
- Ensure a reasonable profit and value through cooperation, teamwork and ongoing partnering

Spirit on the South Boston Interchange (West)

- Open communication and honest negotiations with mutual respect, trust and pride in the project
- Celebrate the successes and have fun building the job

FIGURE 1. A sample CA/T Project partnering agreement.

workshop, each group presents its action plan to the entire group of participants for discussion and input.

The participants are also required to develop an issue resolution model for the project. This model identifies the people from each organization who will be responsible for resolving issues from the field level all the way up to the top managers. It usually identifies time frames by which issues should be resolved or delivered to the next level for resolution. The purpose of this model is to acknowledge to employees that problems and disagreements will come up during the contract and that team members are expected to work with their counterparts to resolve any problem in a timely manner. Issues and problems cannot be left unresolved for long. Unresolved issues are one reason many projects fail. Partnering will not eliminate all problems, but it provides tools to help guide team members in their behavior and enables them to resolve issues as quickly as possible. Figure 2 (on page 56) shows a sample issue resolution model used on the CA/T Project.

The workshop generally concludes with a group photograph and the signing of the partnering agreement.

Partnering Steering Committee. A steering committee composed of one person from each organization is formed for each partnership. This committee is responsible for following up and ensuring the completion of all action plans, introducing new players to partnering, evaluating the effectiveness of the team at meeting its goals and addressing new issues or problems that have arisen. This group meets quarterly.

Follow-Up Workshop. The CA/T Project encourages a follow-up workshop six to nine months after the initial workshop. The purpose of the follow-up workshop is to reinforce the goals and attitudes developed at the initial workshop and to address any new issues that have come up. The workshop lasts one day and is usually held at a neutral site with the original facilitator brought back to conduct the workshop.

Crane *et al.* conducted interviews with various companies implementing partnering and reported that while the cost of partnering is difficult to establish, it ranges from 0.25 to 2 percent of the project cost.[1] This figure is consistent with the experience in the CA/T Project. The direct expense costs of running a two-day initial workshop for about 30 persons is approximately $7,000 (split 50-50 between the two main organizations involved). The cost of the follow-up workshop is about $4,000 or $2,000 per organization.[5] These numbers are the direct expense costs and do not include the salaries of the participants. In a $1 million project, the cost of partnering is approximately 1 percent of the contract value. On larger projects this cost is relatively smaller.

Partnering Effectiveness on the CA/T Project

Contracts Data Collection & Analysis. In order to assess the effectiveness of partnering on the CA/T Project a study was conducted. The approach methodology consisted of reviewing all the contracts involving the construction of permanent structures that were completed at the time when this study was conducted in the summer of 1996. By that time, thirteen contracts involving permanent construction had been completed. Eight of these contracts participated in the partnering program and five did not. Further review of these contracts showed that four contracts were extremely large and complex compared to the rest. In order to eliminate any impact that the size of the contract might have on the results of comparison, these contracts were not considered in the analysis. The remaining nine contracts consisted of four partnered and five non-partnered projects. Since most of these contracts were utility relocation and construction projects, the types of contracts considered in this study were compatible. Table 2 lists the partnered contracts along with some relevant project data. Table 3 provides similar information on the non-partnered contracts.

For each of the projects reviewed, cost growth, schedule growth, change order volume, value engineering savings and safety data were collected. These parameters are similar to those reviewed and compared in previous research.[6,8] Table 4 presents the results of the investigation. In that table the following definitions are used:

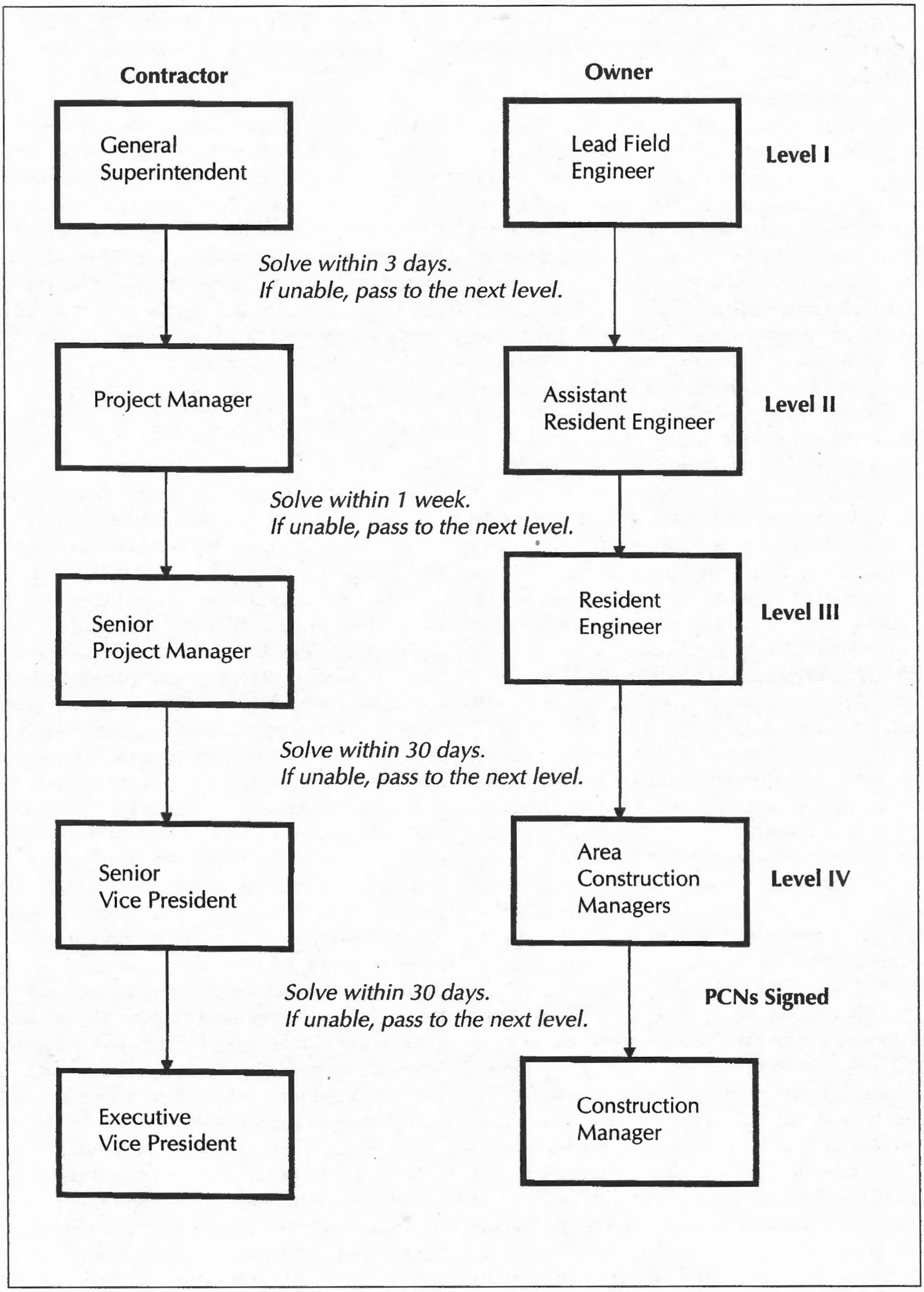

FIGURE 2. A sample contractual issues resolution process on the CA/T Project.

TABLE 2.
Summary of Partnered Projects

Project Number	Type of Work	Original Bid ($)	Duration (Months)
1	Rerouting of all utilities on several streets involving open cut, slurry wall & jacked pipe construction methods	23,458,000	29
2	Relocation of sewer lines in downtown streets using open cut & jacked pipe construction methods	14,562,000	16
3	Relocation of all utilities on several downtown streets using open cut & jacked pipe construction methods	3,798,000	15
4	Relocation of all utilities in several downtown streets using open cut & slurry wall construction methods	5,627,000	15

- *Cost Growth (%).* The ratio of the difference between the final cost and the original bid price to the original bid price. The final cost included all costs such as change orders, overruns or underruns in unit price items, police details, etc.
- *Schedule Growth.* The ratio of the difference between the final duration and the original contract duration to the original contract duration.
- *Change Order Volume.* The ratio of all the change orders to the original bid price. Since most of the contracts reviewed in this study involved unit-price items that could overrun or underrun, change order costs were different from the final costs used in the cost growth calculation.
- *Value Engineering Savings.* The ratio of total dollar value savings to the original bid price.
- *Safety.* Two rates were used to measure safety on the projects. The first rate was the OSHA Recordable Injury (OSHA REC) rate that includes all recordable injuries whether or not employees missed work. The second rate was the OSHA Lost Work Day (LWD) rate, which is a measure of injuries that result in lost work days. The LWD rate generally represents more severe injuries.

TABLE 3.
Summary of Non-Partnered Projects

Project Number	Type of Work	Original Bid ($)	Duration (Months)
1	Excavation, grading & paving of approximately 6,000 feet of a two-lane roadway	8,818,000	18
2	Relocation of an existing railroad track & modifications to an overhead bridge	1,748,000	10
3	Relocation of utilities & construction of sewer lines using jacked pipe method	5,148,000	12
4	Relocation & construction of combined sewer overflow & concrete culverts using open cut excavation & slurry wall	20,494,000	16
5	Relocation of water & other utilities & installation of a gas line using open cut excavation	2,260,000	14

TABLE 4.
A Comparison of the Performance Parameters Between Partnered & Non-Partnered Projects

Project Number	Cost Growth (%)	Schedule Growth (%)	Change Orders (%)	Value Engineering Savings (%)	OSHA REC Rate	OSHA LWD Rate
Partnered						
1	30	-18	13	0.45	30.1	16.9
2	21	43	16	2.67	18.6	10.5
3	66	89	44	0.00	8.1	8.1
4	16	6	7	0.00	11.1	11.1
Average	33	30	20	0.78	17.0	11.7
Non-Partnered						
1	23	20	23	0.00	20.1	6.0
2	6	13	4	0.00	—	—
3	22	20	18	0.00	23.6	0.0
4	73	54	63	1.88	15.6	5.6
5	113	62	78	0.00	23.8	11.9
Average	47	34	37	0.38	20.8	5.9

Almost all these projects were subject to high levels of risk and uncertainty — a given for utility relocation work, especially in old urban areas where information about the location and condition of utility lines is usually incomplete or, in many cases, non-existent. Due to incomplete or missing information, utility relocation and construction projects usually carry some of the largest contingency rates.[13,14] Given these uncertainties, relatively large cost and schedule growth in these projects were not unexpected. Another interesting feature of these nine projects was that no disputes went to Dispute Review Boards or to the courts.

The data in Table 4 reveals that partnered projects outperformed non-partnered projects in virtually every category — including cost growth, schedule growth, change order volume and value engineering savings. The only exception was the LWD category, where partnered projects seem to fare worse than non-partnered projects. It would be difficult to assert that the reason for the superior performance of the partnered projects was due only to the partnering process. Every construction project is unique, after all, and many other parameters (such as the individuals running the projects, location and other external factors) can impact project performance. On the other hand, this study tried to compare projects that were similar in organization (same owner and construction manager), type and size. By making the projects as similar as possible, it was hoped to eliminate, or reduce, any potential for bias. A formal statistical analysis was conducted on the data but it failed to detect a significant difference between the partnered and non-partnered data, mainly because of the small number of data.[5] The small amount of data also contributes to the increased sensitivity of the data. The addition or deletion of a single contract can affect the results.

Since the CA/T Project includes numerous large and complex contracts, a second analysis was conducted that included data from the four large partnered contracts that had been removed from consideration in the previous analysis. The results of this second analysis were quite similar to the previous results in the categories of cost growth, change order volume, value engineering and safety (see Table 5). The schedule growth of all partnered con-

TABLE 5.
A Comparison of the Performance Parameters Between Partnered & Non-Partnered Projects, Including Four Large Projects Not Included in Table 4

Project Number	Cost Growth (%)	Schedule Growth (%)	Change Orders (%)	Value Engineering Savings (%)	OSHA REC Rate	OSHA LWD Rate
Partnered						
1	30	-18	13	0.45	30.1	16.9
2	21	43	16	2.67	18.6	10.5
3	66	89	44	0.00	8.1	8.1
4	16	6	7	0.00	11.1	11.1
Partnered but Excluded From Table 4						
5	11	16	9	0.27	12.0	6.9
6	34	45	30	0.00	16.4	5.9
7	33	44	28	0.21	20.0	15.0
8	49	56	30	0.62	29.4	25.8
Average (of all 8)	32	35	22	0.53	18.2	12.5
Non-Partnered						
1	23	20	23	0.00	20.1	6.0
2	6	13	4	0.00	—	—
3	22	20	18	0.00	23.6	0.0
4	73	54	63	1.88	15.6	5.6
5	113	62	78	0.00	23.8	11.9
Average	47	34	37	0.38	20.8	5.9

tracts (including the four larger contracts) increased slightly, making it comparable to the schedule growth of the non-partnered contracts. This outcome is plausible since large complex contracts would seem to have more potential for schedule growth.

Survey. In order to obtain more information on the impact of partnering on the CA/T Project, a questionnaire was sent to the various parties involved in the project. It consisted of a few multiple choice questions followed by two questions asking the respondents to identify specific negative or positive aspects to partnering (see Table 6). The questionnaire was sent to:

- Nine area managers from the MHD, FHWA, and the joint venture;
- Fifteen joint venture resident engineers; and,
- Eleven contractor project managers.

The response rate was 77 percent (27 persons out of 35).[5]

Table 6 summarizes responses to questions in the survey. The lowest rating was on the issue of trust. Some comments indicated that there is distrust when money is involved. The joint venture and the contractors reported that trust between engineer and contractor was not very good. One positive comment was that partnering led to fewer written materials and more verbal agreements that the parties honored.

Communication — another area that partnering advocates contend benefits from the process — was rated excellent to good by most respondents. Although almost everybody agreed that communication was good or excellent at the Resident Engineer/Project Manager level and above, some reported that communication was not very good below these levels —

TABLE 6.
A Summary of the Survey Results

Questions	Area Managers	Resident Engineers	Contractor Project Managers
Is partnering beneficial?	Yes (100%)	Yes (67%) No (33%)	Yes (100%)
Rate communication on your contract.	Excellent to good (100%)	Excellent to good (75%) Fair to poor (25%)	Excellent to good (56%) Fair to poor (44%)
Rate trust on your contract	Excellent to good (86%) Fair to poor (14%)	Excellent to good (50%) Fair to poor (50%)	Excellent to good (50%) Fair to poor (50%)
Rate the upper management support for partnering.	Excellent to good (88%) Fair to poor (12%)	Excellent to good (67%) Fair to poor (33%)	Excellent to good (88%) Fair to poor (12%)
Is the issue resolution model useful?	Yes (100%)	Yes (90%) No (10%)	Yes (80%) No (20%)

that the field and office staff do not communicate that well.

The survey also asked the respondents to cite negative and positive aspects of partnering.

The important negative issues are summarized as follows:

- Several people from the owner's side reported that they felt partnering led to compromising with, or giving in to, the contractor even when it was unjustified.
- Few reported that contractors view partnering as a way to maximize their potential profits on change issues.
- Some contractors reported that the owner was too lenient with abutters and third parties in granting extras that drove up the cost for the contractors and that could impact schedule.
- Staff turnover during a contract was cited as undermining the effectiveness of partnerships and one manager reported that follow-up on issues did not occur because of such turnover.
- A few respondents felt some people view partnering as a means to waive the contract requirements.
- Some reported that partnering opens communication at all levels that can lead to problems if unresolved issues are not moved up the chain of command quickly for resolution.

Most of these issues could have been avoided if the tenets of partnering were followed. For example, inappropriate compromising violates the win-win aspect of partnering. All parties should strive to come up with solutions that are beneficial or better for everybody in a fair and equitable way. Also, partnering never encourages waiving contract requirements; rather, it allows all parties to talk openly about alternative ways to meet requirements.

The respondents also noted positive outcomes of the partnering process:

- Many managers reported that major claims were avoided due to partnering.
- Many respondents felt that communication had improved, leading to better coordination among all of the parties involved, including impacted abutters or follow-up contractors.
- Many managers reported specific instances where everyone worked together to meet schedule requirements or resolve field problems quickly.

Summary & Conclusions

In order to assess the effectiveness of partnering on project performance, performance data was collected on nine CA/T Project contracts that had been completed by the summer of 1996. Most of these contracts involved utility relocation and construction. The cost of these projects ranged from $1.7 to $23.4 million. Even though the results could not be statistically validated due to small sample sizes, four partnered projects performed better than five non-partnered projects in virtually every category measured. Cost growth averaged 33 percent versus 47 percent for partnered and non-partnered projects, respectively. Schedule growth averaged 30 percent versus 34 percent for partnered and non-partnered projects, respectively. And change order growth averaged 20 percent versus 37 percent for partnered versus non-partnered contracts, respectively. Also, partnered projects had more value engineering proposals submitted with larger cost savings compared to non-partnered projects. Safety, however, produced mixed results in that partnered projects had fewer OSHA recordable injuries, but non-partnered projects had fewer lost workday injuries.

A survey was also conducted to gather information from managers from owner, contractor and consultant organizations. Results of this survey revealed mixed opinions on the various aspects of partnering. However, most responses were favorable to partnering. Some of the responses from the survey emphasized that for the partnering to be successful all of the involved parties:

- Should not compromise unnecessarily on tough issues;
- Should enforce partnering among field and office staff;
- Should minimize staff turnover on partnered contracts; and,
- Should strive to create an environment of trust among the parties involved.

Based on data to date, partnering appears to be having a positive effect on construction at the CA/T Project. It seems safe to say that the potential benefits of partnering far outweigh the relatively small costs associated with implementing a partnering program on a contract.

NOTES — *Dupont Engineering was the first U.S. business to use partnering with Fluor Daniel. The U.S. Army Corps of Engineers became the first public agency to use partnering in 1988 when it began work on a project with FruCon Construction Corp. The CA/T Project is managed by the joint venture of the Bechtel Corp. and Parsons Brinckerhoff (B/PB). The CA/T Project selected a leadeship training course offered by the Franklin-Covey Leadership Center, based in Provo, Utah. Their program,* The Seven Habits of Highly Effective People, *which was developed by Stephen Covey, was selected because CA/T Project management believes it teaches principles crucial for the success of a partnering effort.*

ACKNOWLEDGMENT — *The MHD Partnering Department was initially headed in 1992 by Larry Bonine, currently Director of Transportation in Arizona. Mr. Bonine has always been a strong proponent of partnering since his involvement with it at the U.S. Army Corps of Engineers. His enthusiasm and expertise paved the way for partnering on the CA/T Project.*

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Structural Failure Investigations

The skills required of a forensic engineer differ from those of a design engineer, but the analysis of a structural failure can provide much benefit in the design and construction of new projects.

GLENN R. BELL

Investigations of structural failures are conducted for a variety of purposes. Most commonly, when a structure collapses there is litigation involved, and the forensic engineer may be retained by a party who represents a plaintiff's or defendant's interest in order to determine what went wrong and who is responsible. A particular challenge for the forensic engineer in this role is not to succumb to pressure to compromise objectivity and impartiality when answering to a client with a particular bias. For failures less catastrophic than a collapse, the forensic engineer may be retained by the owner or manager of a building, or insurance company, to diagnose structural malperformance and prescribe a remedy — litigation may not be anticipated at all. Occasionally, an investigation may be commissioned simply to tell the general public or a government agency what went wrong. The National Bureau of Standards (NBS), now the National Institute of Science and Technology (NIST), has been called upon by government groups to perform in this role. For example, the U.S. Senate and the Mayor of Kansas City asked the NBS to investigate the 1981 walkways collapse at the Hyatt Regency in Kansas City so that the public would have an explanation for this disaster.[1] In addition, the Occupational Safety and Health Administration (OSHA) retained the NBS to determine the cause of the failure of a cooling tower at Willow Island, West Virginia, in 1977[2] and the collapse of the L'Ambiance Plaza in Bridgeport, Connecticut in 1987.[3] The purpose of these investigations was to assist OSHA in assessing fines.

Generally, while the structural engineering profession has no direct means of authorizing investigations to determine what lessons may be learned from failures, many individuals and groups have been active in gleaning what has been learned from investigations conducted for other purposes and disseminating those lessons to the profession. With a breadth of purposes comes a breadth of client types. Some of the types of individuals and organizations that make use of structural investigations are:

- Owners;
- Developers;
- Public and government agencies;
- Plaintiffs in litigation (injured parties);

- Defendants in litigation (parties involved with design, construction, maintenance or operation);
- Tenants;
- Attorneys;
- Insurance companies;
- Materials manufacturers;
- Designers; and,
- Contractors.

Forensic engineers may be called upon to determine two types of causes of failure: *technical causes* and *procedural causes*.

Technical causes are the actual physical proximate causes of failure. For example, the hanger-rod-box-beam connection at Line U2 ruptured. Or, the roof collapsed due to a 150 percent overload from drifting snow. Or, the timber truss failed by buckling of the fourth compression diagonal. Often compounding problems lead to failure, and determining the relative contributions from various structural defects is challenging. Sometimes compound defects are so debilitating that the challenge is not to determine why the structure fell down but rather why it stood for as long as it did.

Procedural causes are the human error, communication problems or shortcomings in design, construction or maintenance that were responsible for the flaws that led to the technical cause. For example, the welding of the hanger-rod-box-beam connections did not meet the design requirements. Or, the structural engineer neglected the effects of drifting snow in the design. Or, the carpenters omitted critical bracing for the truss diagonals.

Often, determining the procedural causes is the more difficult but important aspect of an investigation, particularly for determining the lessons to be learned. Neal FitzSimons has estimated that 90 percent of failures are due not to a lack of technical information, but to procedural errors.[4]

Several available guides for conducting investigations describe particular techniques.[5-12] Similarly, there are available guidelines and standards for material-specific or test-specific methods.

The term *forensic* is often misunderstood since it has two meanings in engineering. In the most literal sense, it relates to court or other public disputes. More generally, and as used by the American Society of Civil Engineers Technical Council on Forensic Engineering (ASCE/TCFE), it means all of the activities involved with investigating the causes of failure or malperformance. Indeed, it is typically the case that only a small fraction of the forensic engineer's work is involved in litigation activities. The latter, broader definition is the focus herein.

Project Initiation

Project Objective & Scope. As with any consulting assignment, the project usually begins with a meeting or phone call during which the potential client describes his or her needs and objectives for the investigation. A few special recommendations for the initial contact in a forensic investigation follow:

- Always check to ensure that there are no conflicts of interest in undertaking the assignment. Until such a check has been made, caution the potential client not to reveal confidential information that could jeopardize the client's position (such as a theory for attacking the litigation) should the engagement have to be declined due to a conflict. Otherwise, the potential client could have grounds to completely disqualify the engineer from the case. (See *Recommended Practice for Design Professionals Engaged as Experts in the Resolution of Construction Disputes).*[13]
- Beware of "takeout moves," wherein the client agrees to engage work, forwards an executed contract, possibly with a small retainer, but then does not extend any work. The purpose is to inexpensively exclude an engineer from working on the behalf of others. It happens.
- Inquire as to the client's motives and the degree to which the engineer will be free to perform an objective investigation in order to form opinions with a reasonable degree of engineering certainty (see Recommendation 12 in Ref. 13). Resolve any scope issues now or refuse the engagement.
- Carefully examine the potential client's objectives. If the client intends to use the

investigation to support a certain point of view in trial, and it is unlikely that the investigation and analysis will be able to support that point of view, inform the client at the beginning. It is always better to be honest up front, even if it means refusing the assignment.

Conflicts of Interest. The guide *Recommended Practice* states:[13]

> Regardless of the expert's objectivity, the expert's opinion may be discounted if it is found that the expert has or had a relationship with another party which consciously or even subconsciously could have biased the expert's services or opinions. To avoid this situation, experts should identify the organizations and individuals involved in the matter at issue, and determine if they or any of their associates have or ever had a relationship with any of the organizations or individuals involved. Experts should reveal any such relationships to their clients and/or client's attorneys to permit them to determine whether or not the relationships could be construed as creating or giving the appearance of creating conflicts or interest.

Conflict avoidance in large organizations is difficult. A computer database of current and past projects can be used by a firm to try to identify potential conflicts.

Establishing the Investigative Plan. To determine the technical causes of failure, the goal of the investigation is to establish:

- The mode and sequence of the failure;
- The demands (loads) acting on the structure at the time of the failure; and,
- The capacity of the structure at the time of the failure.

The process usually involves developing hypotheses regarding the causes of failure and then analyzing and testing those hypotheses. With effort, certain failure theories are eliminated and, it is hoped, in the end, the facts will support one theory. Sometimes the investigation reveals that the demand on a certain part of the structure exceeded its capacity for one and only one failure mechanism and that mechanism is consistent with the evidence of the mode and sequence of the failure. Sometimes the results are not so straightforward.

From the outset, the forensic engineer creates an investigative plan, a common general flow chart for which is given in Figure 1. However, not all investigations entail using every step, and the investigative plan is continuously revised to account for evolving theories and information. Some investigators have developed elaborate flow charts for the investigative process (such as those shown in Blockley[12] and Kaminetzky[14]).

Establishing the Investigative Team

Qualifications of the Investigator. By education, structural engineers are trained generally for the design and construction of new works. To the author's knowledge, no universities offer degree programs in forensic engineering, although a few offer courses in failure causes.

Structural design and structural investigations require very different approaches. The first is a process of synthesis; the second, one of analysis. Design requires, among other things, an ability to create a cost-efficient load-bearing scheme in accordance with a set of "rules" prescribed by building codes for minimal design cost. Simplicity and optimization are paramount. However, investigation requires a structured approach of data collection, and the development and scrutiny of failure hypotheses. Advanced analyses, precision, attention to detail and patience are key. For these reasons, good structural designers do not necessarily make good investigators and vice versa.

The key to proficiency in either discipline is experience, and any individual with interest in structural failure investigations should make a thorough review of available literature. A review of this literature not only provides insight into investigative processes and techniques, but it also demonstrates the common ways that structures fail. A veteran investigator of thousands of failures, Jack Janney, once remarked, "structures nearly always fail by buckling or where loads must turn a corner" (see Figures 2 and 3 on pages 67 and 68, respectively). While quite a generalization, this statement is not far off the mark. It is this type of real-world understanding of why build-

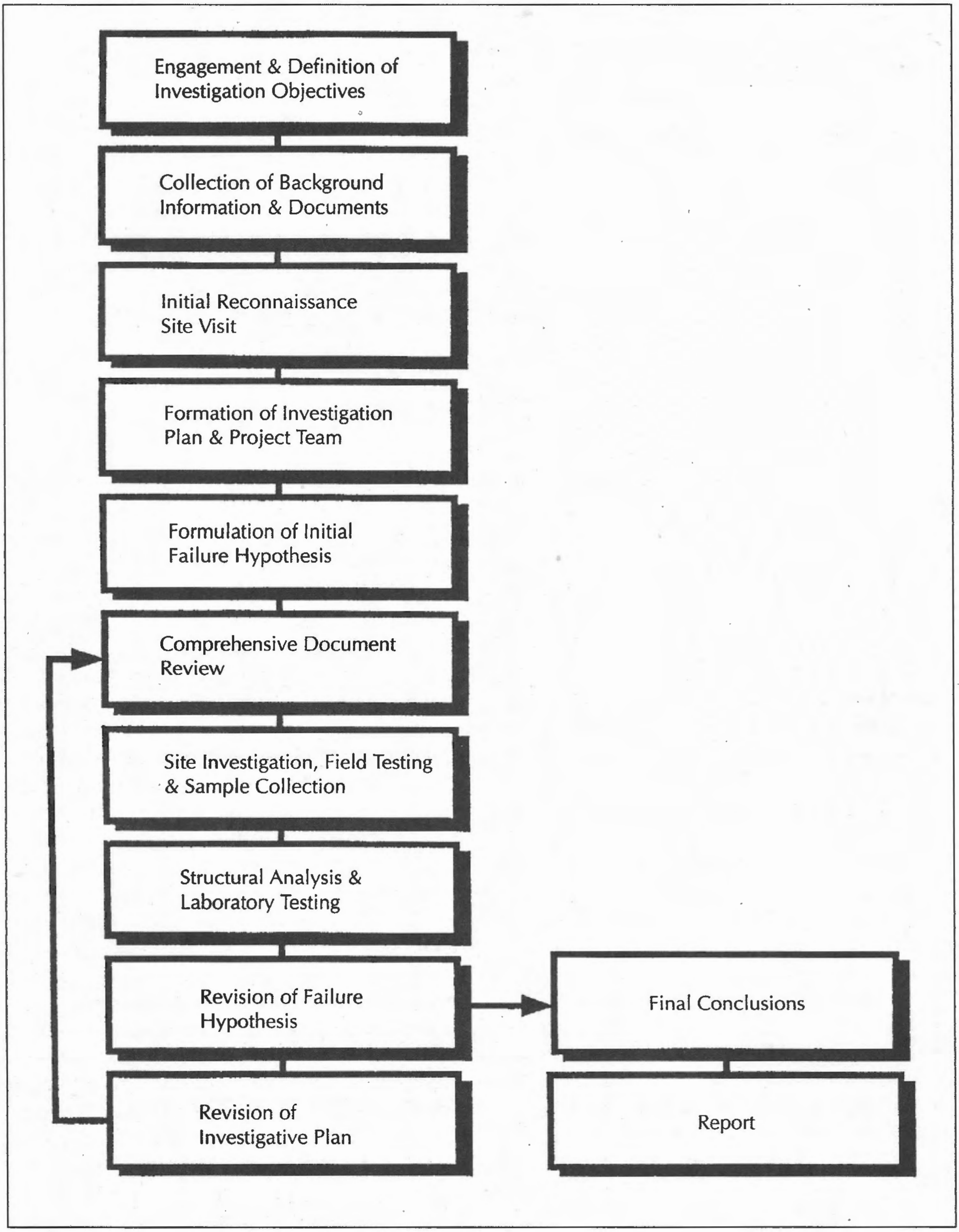

FIGURE 1. The investigative process.

ings stand and why they actually fail that, in part, differentiates a good investigator from a good designer.

In addition to technical skills, the forensic engineer requires outstanding characteristics in the following areas:

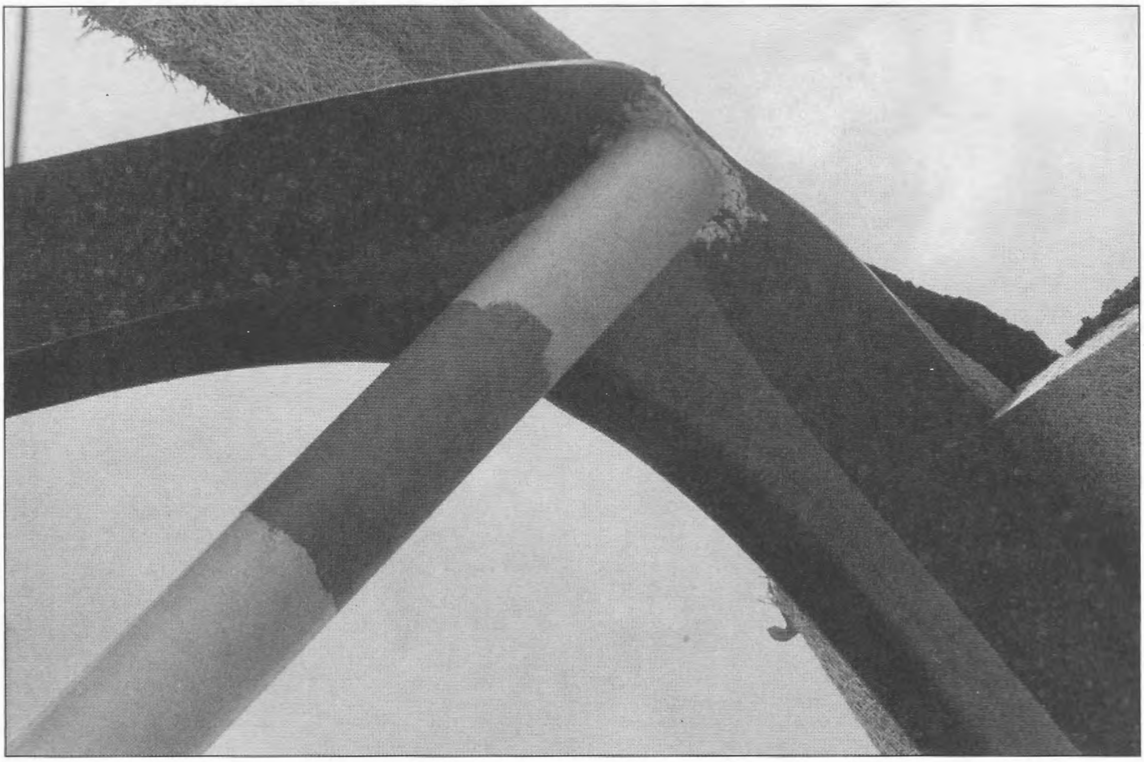

FIGURE 2. Roof failure by buckling of the beam/column joint.

- Credentials that grant credibility to the individual's opinions;
- The ability to convey often complex issues simply and convincingly to lay people;
- Absolute honesty and the ability to work impartially under pressure from individuals with partial interests;
- Stamina and constitution to sustain the stress of litigation proceedings;
- The ability to remain composed under sometimes hostile examination; and,
- When called upon to convey opinions regarding procedural causes of failures, knowledge of the standard of care of practitioners in the industry.

Available Guides. The process of investigating failures will never follow standard procedures. Each investigation is different and requires a tailored approach. Nevertheless, there are some useful guidelines for conducting investigations. The most noteworthy are:

- *Guidelines for Failure Investigation,* by the ASCE/TCFE Task Committee on Guidelines for Failure Investigation;[5]
- *Guide to Investigation of Structural Failures,* by the ASCE Research Council on Performance of Structures;[6]
- *Building Failures – A Guide to Diagnosis, Remedy and Prevention,* by Lyall Addleson;[7] and,
- *Building Pathology, A State-of-the-Art Report,* CIB Report Publication 155.[15]

In addition, there are a number of useful articles on the subject.[9-12,14]

Sources of Failure Information. For anyone interested in the study of failure investigations, the ASCE *Journal of Performance of Constructed Facilities* is highly instructive. Published quarterly, that journal contains case studies of individual failure investigations as well as articles on particular failure issues. In addition, failure books and articles are often published in other industry literature.[16-30]

Some of the most thorough and well documented reports of failure investigations are

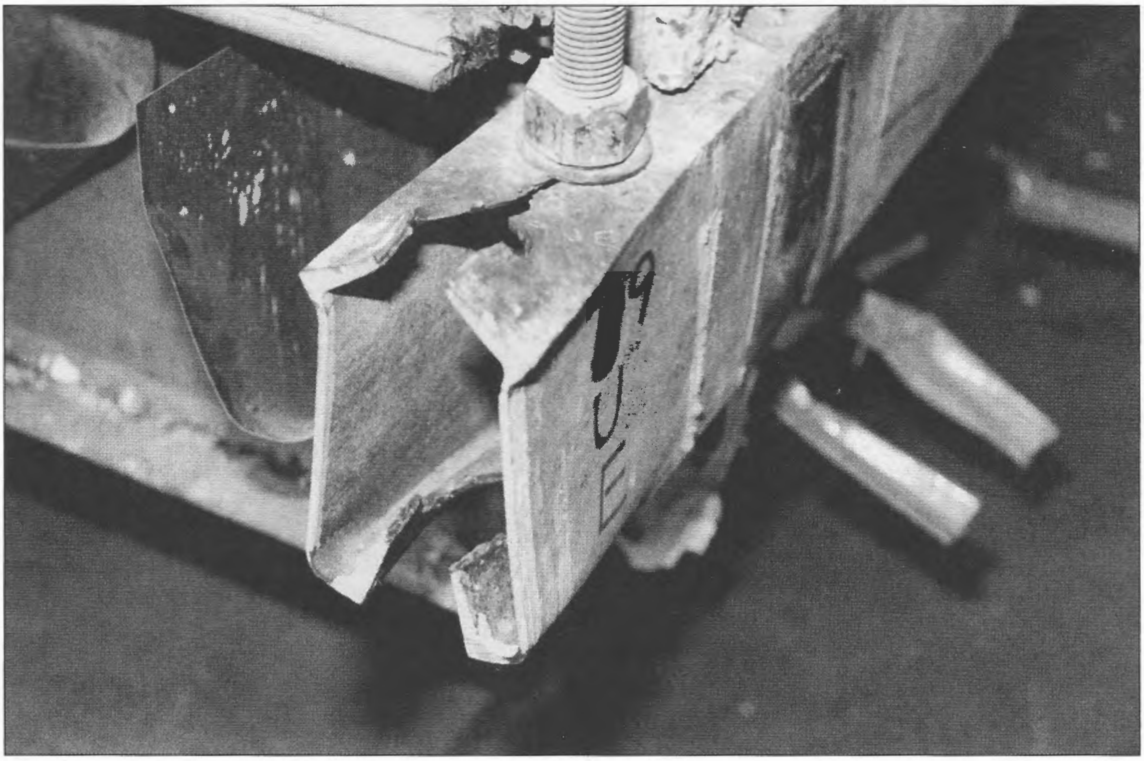

FIGURE 3. Failure by connection tear-out.

those of the NBS/NIST. Among others, the NBS/NIST has investigated the 1981 Hyatt Regency, Kansas City walkways failure,[1] the 1981 collapse of the Harbour Cay Condominium in Cocoa Beach, Florida,[31] and the 1988 collapse of L'Ambiance Plaza in Bridgeport, Connecticut.[3]

Team Organization. In large, complex investigations it is rare for the Principal Investigator (PI) to possess all of the requisite technical skills. Therefore, the PI may rely on specialty subconsultants in such areas as:

- Materials behavior;
- Testing and instrumentation;
- Special loads effects (*e.g.*, wind); and,
- Special analysis techniques.

A comprehensive list of the specialists on which the PI may rely is given in Table 1. The qualities required of these specialists are generally the same as those that are required of the forensic investigator. The forensic engineer should have pre-established relationships with such specialty consultants, so that they may be summoned on short notice when a structure fails.

When working on large, complex cases, strong project management involving the establishment of clear lines of communication and responsibility is essential. Periodic updates of the investigative plan must be conveyed to the entire team. Continuous quality control/assurance over in-house staff and external subconsultants must be exercised.

Cooperative Efforts With Other Investigators. Investigations can be expensive, and available debris for testing and examination limited. For these reasons, investigators answering to parties of different interests sometimes cooperate in the data collection and testing phases of an investigation, which was the case, for example, in the Hyatt Regency walkways collapse, where there were numerous experts representing a number of parties. Critical structural components from the debris needed to be tested destructively. The interested parties assembled and agreed that the NBS would perform the necessary laboratory analysis and testing, using procedures agreed to by all experts. All ex-

TABLE 1.
Specialist Consultants

Aerodynamics	Field testing	Photoelasticity
Aluminum	Fracture	Photogrammetry
Architecture	Geology	Pile driving
Blasting vibrations	Geotechnical engineering/ foundations	Pipelines
Climatology	Glass	Pipes
Cold weather construction	Ground water	Plasticity
Composite materials	Hydraulics	Plastic materials
Computer design	Hydrodynamics	Prestressed concrete
Concrete materials	Impact	Probability theory
Construction equipment & methods	Masonry	Protective coatings
Corrosion	Mathematics	Railroads
Cost estimating	Measurement technology	Shoring
Data systems	Meterology	Stability
Dynamics & vibration	Nondestructive testing	Statistical analysis
Elasticity	Ocean engineering	Steel
Electronics	Offshore construction	Surveying
Engineering mechanics	Painting	Waterproofing
Environmental engineering	Parking engineering	Welding
Fabrication	Pavements	Wind
Fatigue	Petrography	Wood

perts were allowed to witness the testing, and data were shared.

The Investigative Process

Analysis Versus Synthesis. When investigating a structural failure, a forensic engineer cannot think like a designer. Whereas in the design process the designer has the freedom to arrange the structure to behave the way he or she wants, after a structural failure there is no such control — the structure has already behaved the way it wanted.

Building code methods that designers use are assumed to be conservative, but they do not always describe structural behavior well. For example, just because a structural steel beam may be loaded to its theoretical yield point (allowable stress times factor of safety), it cannot be assumed that the beam will collapse. The beam has post-yield capacity; it can strain harden; there may be redundancy and alternate load paths; and, the yield strength is likely to be higher than the minimum specified. The more redundant and ductile the structure, the more likely it will yield, redistribute load and continue to maintain load-bearing ability. The investigator must take all of these factors into account.

Simple and conservative techniques — the hallmark of good design — are not appropriate for investigations. In an investigation, greater precision is required, advanced analysis is often called for, all facts must be verified and any unconfirmed assumptions can lead to costly errors.

Development & Analysis of Failure Hypotheses. A mistake sometimes made by novice and experienced investigators alike is to fail to consider all possible failure hypotheses. All probable hypotheses must be developed and systematically analyzed until they either can be proven or disproved. Key in developing failure hypotheses is to study carefully the configuration of the debris after the failure, and then try to imagine all of the different failure sequences the structure could have undergone to arrive at its final configuration. The structure tells a story that should be listened to carefully.

Establishing the Actions on the Structure. Dead loads are verified by cataloging observations from field investigations. Sometimes it is necessary to weigh existing components, material samples or assemblies. Often dead loads are less than the allowances made during design, but they may be greater. Long-term maintenance and modification can lead to increased dead loads in the form of additional roofing membranes, ceilings or mechanical equipment. Leaky roofs and walls saturate components. In cast-in-place concrete construction, structural deflections due to the "ponding" of wet concrete have led to slabs thicker than required by design.

Live loads, of course, take many forms and often are difficult to verify. Snow, ponded water, furniture and equipment, and human occupancy are the common forms of live load. Cataloging, sampling and weighing, and eyewitness accounts are all available forms of data collection for determining live loads. The increasing use of video security surveillance cameras often affords an invaluable source of information regarding loads and sequences of failures. Load effects other than those caused by gravity also cannot be overlooked. They may include temperature, shrinkage and creep, wind and seismic, vehicular impact, vibrations from equipment and foundation settlements — to name a few. Live load behavior may vary from simplified assumptions. For example, some materials will tend to arch over relatively flexible structural components.

Establishing the Capacity of the Structure. Usually the first step in determining the capacity of the structure is to review the structural drawings for the project. While drawings can be a great time-saver in establishing the overall structural configuration, they can lead an investigator down an erroneous path if they are relied on without critical verification. Dimensions and member sizes often must be confirmed. Material strengths may require certification. The amount of verification required to reach conclusions with a reasonable degree of engineering certainty may be enormous; occasionally it is practically impossible.

Structures may deteriorate from the as-built condition from a number of effects such as:

- Water intrusion and other corrosive effects;
- Fatigue;
- Damage from nearby blasting, traffic vibrations or adjacent construction; and,
- In concrete, material degradation from chloride attack, alkali-silica reaction or delayed ettringite reaction.

Following documentation of the as-built condition, the determination of strength may come from load testing, from calculations, or both. It should be noted that non-structural elements, most notably exterior walls and interior partitions, may play an unintentional role in the behavior of the structure by interacting with the structural frame.

Advancement of Failure Hypotheses. Over the course of an investigation, failure hypotheses are continuously tested by the facts and the results of testing and analysis. Some hypotheses may be disproved and dropped, while new ones may be advanced. It is generally advisable to assemble the investigative team shortly after the initial site investigation for a brainstorming session on failure hypotheses.

Document Review

Sources of Project Documents. Project documents are key to understanding not only how the structure was built but also how it was maintained and modified over time. Without such documents the job is difficult for a project of any complexity. Whenever possible, the investigator should obtain and review at least the most fundamental design documents prior to initial site investigation. Project documents are also key when the forensic engineer is called on to opine on the procedural causes of the failure in that they provide insight into the actions of those responsible for the design, construction and operation of the facility.

Common sources of project documents are from:

- Architects and engineers involved in the original design, modification or repair of the facility;
- Past and present owners;
- Past and present building managers;
- General contractor and/or construction manager for the original construction, modification or repair of the facility;
- Subcontractors involved in the original construction, modification or repair of the facility;

TABLE 2.
Project-Specific Documents Used in Investigations*

Contract drawings (including all revision issues thereof)
- Structural (including progress prints)
- Architectural (including progress prints)
- Mechanical (HVAC)**
- Electrical**
- Plumbing**
- Lighting**

Contract specifications
- Technical sections of interest
- General conditions
- Supplementary general conditions
- Special conditions

Contracts
- Owner/architect
- Architect/structural engineer
- Contract revisions
- Addenda
- Bulletins
- Field directives
- Change orders
- Any correspondence authorizing change to the structure from the contract requirements

Shop drawings & other submissions
- Structural steel (detail drawings & erection drawings)
- Bar joists & prefabricated trusses
- Metal decking
- Reinforcing bar
- Product data

As-built drawings

Field & shop reports (including construction photos)
- Structural steel inspection laboratory (including weld & bolt inspection)
- Concrete inspection laboratory (reinforcing steel, formwork, concrete)
- Concrete mix designs
- Clerk of the works
- Structural engineer
- Architect
- Construction supervisor's daily log
- Local building inspector
- Owner's or developer's field inspectors

Materials strength reports or certification
- Concrete compressive strength
- Masonry prism strength
- Steel mill certificates
- Welding procedures (*e.g.*, type of electrodes, required preheat)
- Fastener certification
- Results of special load tests

Project correspondence
- Owner/consultant
- Intraconsultant
- Owner/contractor
- Consultant/contractor
- Transmittal/records
- In-house memoranda
- Records of meeting notes
- Records of telephone conversations

Consultant reports
- Feasibility studies
- Progress reports
- Soils consultant reports (including boring logs)

Calculations
- Primary structural engineer
- Reviewing structural engineer
- Specific subcontractor's engineers (where required by contract)

Maintenance & modification records

Notes: *The scope will vary depending on the investigator's assignment.
**Assist principally in establishing dead loads.

- Developer of the facility;
- Construction mortgagee of the facility;
- Materials or systems suppliers for the original construction, modification or repair of the facility;
- Previous or other current investigators;
- City, town or state building departments; and,
- Testing agency involved in the original construction, modification or repair of the facility.

Types of Available Documents. Table 2 contains a comprehensive list of documents that may be useful for failure investigations. Documents of the non-structural trades — architectural, mechanical/electrical, etc. — are often useful for determining dead loads on the structure. In addition, non-structural elements may play an unintentional role — positive or negative — in the structure's loadbearing capacity.

The importance of materials produced subsequent to the issuance of the design documents — addenda, shop drawings, bulletins, and field inspection reports — should not be underestimated since they often provide critical information about the departure of the structure from the structural drawings. In addition, as-built drawings are rarely accurate.

Field Investigation

Access to & Control of the Site. Particularly following a large, catastrophic failure, the PI must verify his or her rights and limitations regarding access to the site and activities there. (Often disaster sites are controlled by local or state police or national guard.) Who has authority over site access and who is authorized to admit investigators to the site? Are there limitations on where the investigator may go and may do? Does the investigator have authority to alter evidence by moving debris or collecting samples?

Site Safety. Collapse scenes can be dangerous places (see Figure 4). Once, during an investigation of the collapse of an earth-covered garage, a second section of the garage collapsed.[32] Thus, the leading concern of every team member must be the safety of the team as well as others at the site. There are other hazards in addition to direct falling hazards that are of concern. Sometimes failures lead to the release of environmental hazards. Also, investigators may be entrapped in confined spaces. Many OSHA regulations define procedures for construction site safety, training and certification that are relevant to field investigations.

Where rescue operations are ongoing during field investigations, such operations must take precedence over the investigator's interest in data collection. If the investigator arrives on site shortly after the failure while rescue operations are underway, it may be necessary to suspend investigative efforts to lend special expertise to the rescue effort.

Sample Removal. The PI establishes the overall project protocol for identifying, cataloging, removing, shipping and storing samples. It is recommended to mark each sample with a permanent marker and then photograph it before it is removed (see Figure 5). Note any existing damage or distinguishing characteristics before removing the artifact from the structure. Samples that may deteriorate quickly after removal may have to be environmentally protected. Fracture surfaces may be sprayed with a clear acrylic coating, for example. Moisture-sensitive materials may be placed in sealed bags or other containers, sometimes with desiccants. It is important to maintain a traceable chain of custody of samples so that the sample's origin and handling can be verified without question.

Required Scope of Observations & Sampling. The sampling program should be based, in scope and content, on the presumed failure hypotheses. The number and location of the samples should be carefully planned and will depend on a number of factors such as:

- The variation from sample to sample;
- The degree of reliability required in the results;
- Whether or not there are any explainable trends in the test results (*e.g.*, differing batches of concrete); and,
- The size of structure.

In straightforward cases, the number of samples may be established from statistical principles such as set forth in Ang and Tang[33] or ASTM E105[34] and ASTM E141.[35] Material-specific recommendations are also available in ASTM and other standards.

Observations & Documentation. The PI establishes the overall grid/identification system for the structure. The PI also determines the procedures for sample cataloging, photograph identification, observations openings, etc.

The PI should visit the site early in the process (during the initial site visit if possible) to gain general familiarity with the site. It is important to establish to the extent possible the degree to which the debris may have been modified by others. Subsequent members of the team should similarly obtain a general overview of the site before detailed examination. Each investigator should have his or her own kit of basic tools as well as standard safety

FIGURE 4. Failure sites can be dangerous places.

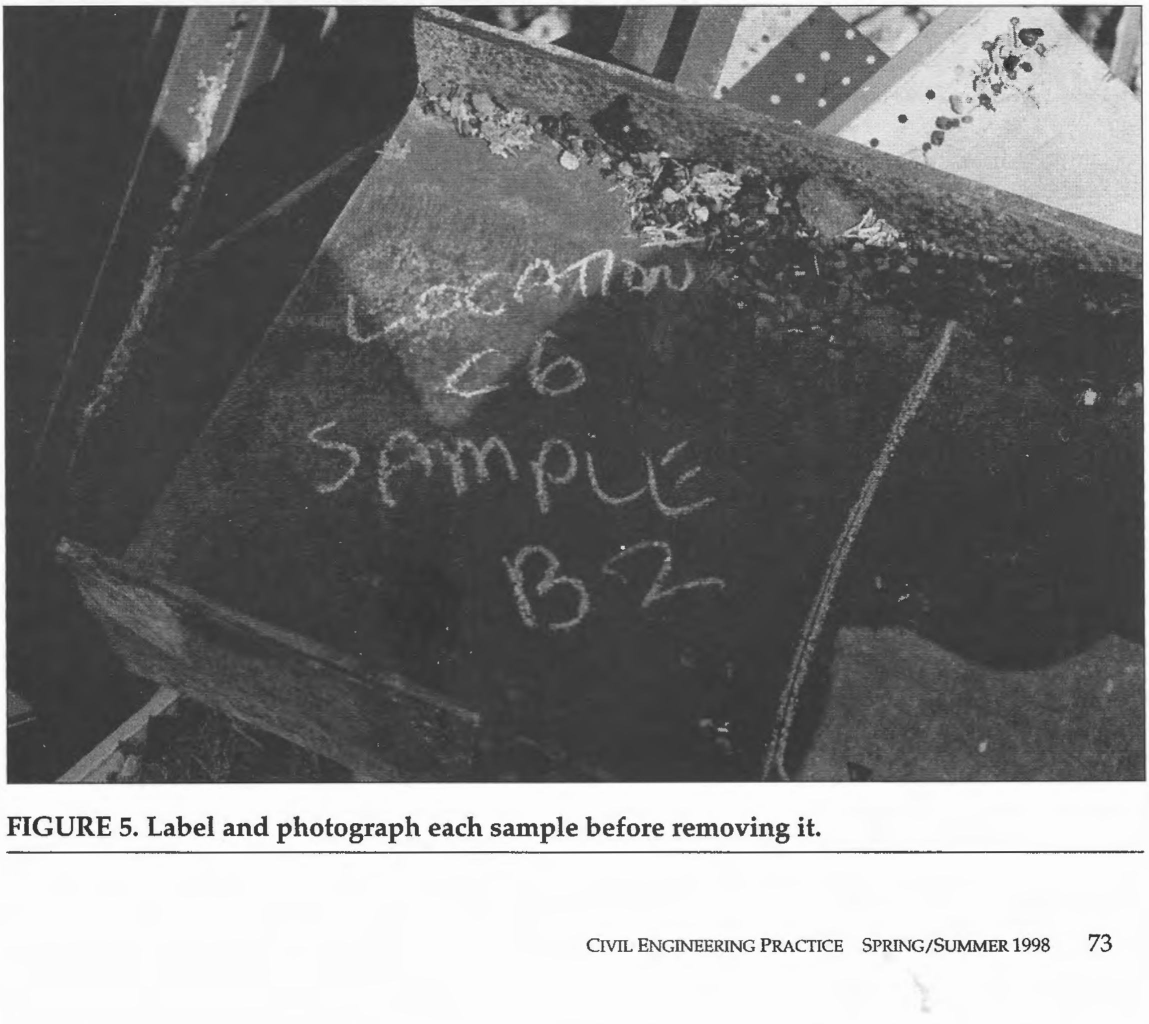

FIGURE 5. Label and photograph each sample before removing it.

TABLE 3.
Small Tools & Equipment Used in Field Investigation

Measurement
- 10-inch dial caliper
- 12-inch steel ruler
- 20-foot tape
- 100-foot tape
- Optical comparator
- Tape-on crack monitors

Tools
- Hammer
- Screwdrivers
- Prybar
- Pocket knife
- Flashlight

Photographic
- Film
- Camera
- Lenses
- Flash
- Batteries
- Lens papers

Clothing
- Hardhat
- Coveralls
- Steel-toed workboots
- Gloves

Stationery
- White-lined paper
- Calculation pad
- Architect scale
- Pencil & leads
- Eraser
- Field notebooks
- Triangles
- Felt markers
- Clipboard
- Lumber crayons

Books
- AISC manual
- ACI code
- Other applicable failure guides

Other
- Calculator
- Stick-on labels
- Wire-on labels
- Plastic sample bags
- Duct tape
- Job file
- Spray paint
- Dictation recorder & tapes

gear (*e.g.*, hardhats and steel-toed shoes). A suggested equipment list is given in Table 3. Field support specialists usually included on a site investigation are:

- Surveyors;
- Concrete coring or sawing technicians (for sample removal);
- Welders (for sample removal);
- Photographers;
- Crane operators;
- Shoring specialists;
- Field and laboratory testing technicians;
- Measurement technicians; and,
- Witness interviewers.

Investigators use a number of techniques for recording field observations and activities. Some keep separate logs of samples, sketches, discussions and general observations. It is preferable that each team member keep a running diary of all field activities, for example in a spiral bound notebook. That way there can be no question as to who was responsible for what observation and at what point in time the observation was made. It is often important to know at what stage or in what context various activities took place. Also, it is much less likely that notes will be misplaced. Common field activities that require recording are

- Sketches of the overall failed configuration;
- Observation of the behavior of adjacent construction during and subsequent to the failure;
- Detailed sketches of critical members and connections;
- Inventory of construction materials to establish dead loads;
- Observation of deterioration;
- Information regarding detailed as-built conditions, including plan and detail dimensions;

- Description of fracture surfaces;
- Notes of samples removed;
- Procedures and results of field tests;
- Indications of environmental conditions acting on the facility at the time of failure;
- Log of photographs; and,
- Notes of conversations with others.

The individual logs or summaries of observations of activities of many investigators can be compiled at a later time from these individual diaries. Sketches and photographs are better than lengthy verbal descriptions (either in writing or tape recording) since they can record more information in a shorter space and are less likely to be misinterpreted.

The speed of observation and data collection may be important in an ever-changing site where rescue operations are ongoing and evidence is being destroyed. The experienced investigator quickly assesses the probable failure hypotheses and targets the field work accordingly.

Field observations are made and recorded on three scales:

- *Overall Configuration:* How did the structure fail? Note movements from initial position and relative positions of components. What is the relationship of damaged and undamaged components? Examine the interfaces of damaged to undamaged components.
- *Member & Connection Configuration:* How are members bent and fractured? Examine fracture surfaces.
- *Materials:* Is there degradation (corrosion, spalling, cracking, rot)? Are there signs of distress (*e.g.*, flaking paint)?

Photography is an essential recording medium, and, while some investigators prefer to use professional photographers, others prefer to take their own shots. The investment in good 35 mm camera equipment and in the time to develop photographic skills may be worth it. Videos are useful to convey action, but video cameras can be more cumbersome to use.

Early in the investigation, good overall aerial shots are invaluable to establish the overall failed configuration and conditions at the site. Such shots may be obtained from an adjacent building, from an aerial lift or from aircraft.

Field Tests. Field testing generally falls into two types: load tests and materials tests. Load tests are useful when an undamaged portion of the structure remains that is representative of the failed section (see Figure 6). They are particularly useful when the structure is severely deteriorated. However, they can be expensive, particularly when several tests are required to obtain statistical significance. Some things to bear in mind regarding full-scale load testing are:

- A number of loading methods are available, including hydraulic jacks, mechanical jacks, water or other weights, and air bags.
- Redundancy in instrumentation is helpful to ensure reliability in results.
- If possible, calibrate equipment before and after testing.
- Safety is critical. Have a safeguard (such as shoring or immediate load relief) in place in the event that the structure begins to fail catastrophically.
- In cases involving many parties in a litigation, it is often appropriate or even required to afford other parties the opportunity to witness tests.
- The portion of the structure being tested must be isolated from structural and nonstructural elements that are not part of the test.
- Some form of back-up or verification of the test results are advisable, either corroborating calculations or another form of test.

ASTM Publication STP 702, *Full-Scale Load Testing of Structures,*[36] provides additional information on this subject. There are also a number of ASTM standards on material or assembly-specific tests.[37-43]

In-field materials tests are numerous and are set forth in many documents. Two comprehensive guides are ANSI/ASCE 11-90, *Guideline for Structural Condition Assessment of Existing Buildings,*[44] and the Institution of Structural Engineers, *Appraisal of Existing Structures.*[45]

Eyewitness Accounts. Eyewitness accounts may not be fully reliable. This unreliablity is not because people are intentionally dishonest, but because most lay observers are not trained

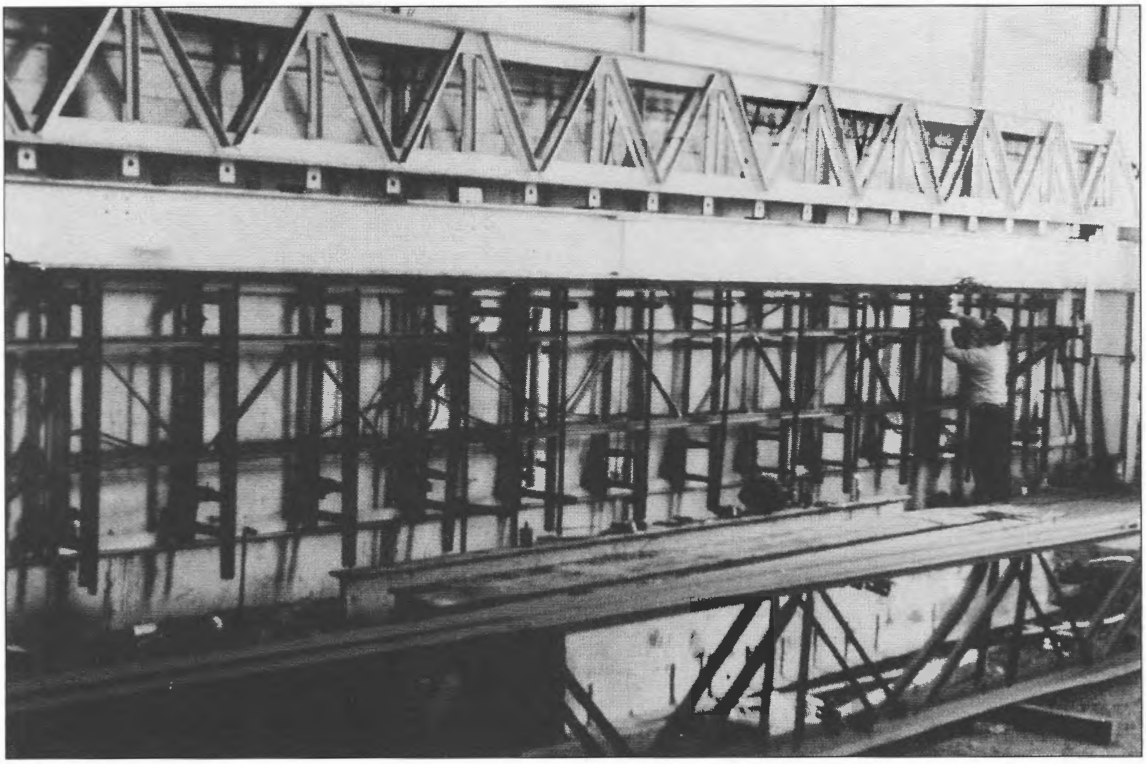

FIGURE 6. Full-scale load testing of a bar joist.

in structural engineering, and the experience of witnessing a traumatic collapse can leave memories distorted. Nevertheless, eyewitness accounts can be useful for obtaining clues and for corroborating other evidence. Janney provides useful guidelines for gathering and evaluating eyewitness accounts.[6]

Laboratory Analysis

Materials Testing. The testing of materials samples that have been removed from the structure may take many forms.

Some of the more common laboratory techniques for the testing of metals are:

- *Basic Mechanical Properties:* yield and tensile strength, elongation, reduction of area, modulus of elasticity, fatigue properties.
- *Fractography:* failure analysis of fracture surface, usually with an optical or scanning electron microscope (see Figure 7).
- *Fracture Toughness:* Charpy V-Notch, fracture toughness, nil-ductility transition temperature.
- *Welding:* radiography, visual, dye penetrant, ultrasonic, magnetic particle, eddy current, metalograph.
- *Hardness:* Brinell, Rockwell, Vickers, and Knoop.
- *Metallurgy & Quantitative Analysis:* Chemical composition, grain analysis, phase type, flaw detection.

Some of the more common laboratory techniques for the testing of concrete and other cementitious materials are:

- *Basic Mechanical Properties:* compressive strength, tensile strength, shear strength, modulus of elasticity, density, bond strength, fatigue strength, abrasion resistance.
- *Dimensional Stability:* creep and shrinkage, coefficient of thermal expansion.
- *Petrographic Analysis:* quantitative analysis, air content, degree of hydration and carbonation, alkali-carbonate reaction, alkali-silica reaction, cement aggregate reaction, cement content, soundness, water/cement ratio, sulfate attack.

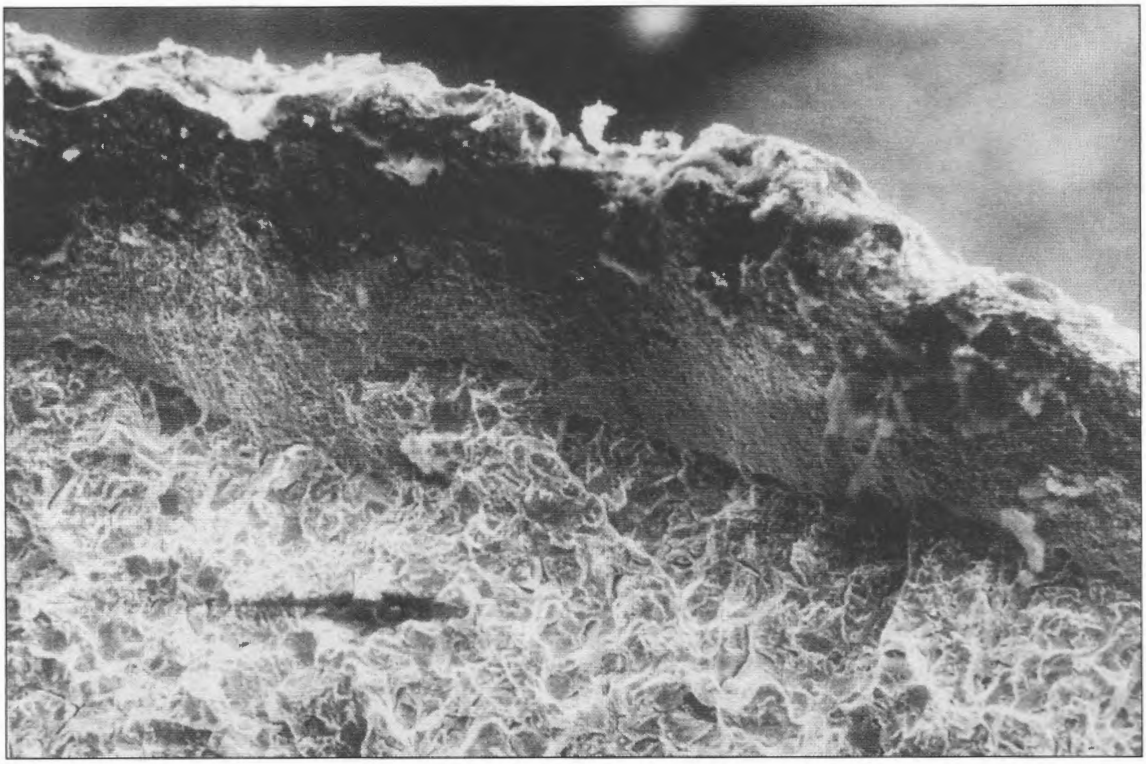

FIGURE 7. A scanning electron micrograph of a fracture surface.

- *Corrosion & Durability:* Permeability, half-cell potential.

Some of the more common laboratory techniques for the testing of wood are:

- *Basic Mechanical Properties:* tensile, shear, compressive, and bearing strength; modulus of elasticity, density.
- *Dimensional Stability:* creep and shrinkage, moisture content.
- *Presence of Decay:* microscopic inspection.

Component Testing. Load testing may be performed on components removed from the field or on mock-ups made in a laboratory. A few recommendations follow:

- Component testing is subject to many sources of error just as are calculations. In particular, the modeling of the test boundary conditions is critical to obtain realistic results.
- Follow established procedures (such as ASTM standards) wherever possible. If there must be any deviation from accepted standards, do so understanding fully the consequences, and be prepared to defend the reasons.
- An individual who is prepared to testify as to the authenticity of the test procedures and results must witness the tests.
- Maintain all test equipment in good working order and make sure it is properly calibrated.
- Use redundant checks on the test results by corroborating calculations or conducting alternative tests.
- The number of tests must be consistent with the investigative objectives for a high level of confidence.

Structural Analysis

Methods. Calculations are almost always required to determine the loads acting on the structure and its resistance. In many cases, simple hand calculations suffice and may be used instead of complex computer analyses . Often, however, it is necessary to resort to computer methods, such as finite-element or finitedifference methods. Structural failures, of course, often result in material and geometrically non-linear behavior, which can be handled directly or indirectly by many finite-element techniques. In many cases, however, non-linear behavior can be sufficiently described by hand methods. A few general recommendations regarding calculations follow:

- Great care is required in complex computer analysis. Programs should be prequalified and their limitations understood. Models must capture all important structural actions and their input must be verified. The mathematical "goodness" of the solution should be verified and the results scrutinized. Computer analysis should be approximately checked by hand techniques.
- Secondary effects of temperature, creep, foundation settlement, stresses induced by construction sequence and eccentricities are often neglected but may be quite significant.
- In reviewing structural designs, do not get hung up in exhaustive documentation of simple code violations that have no causal relationship to the failure.[46]
- Scrutinize all of the parameters in the resistance relationships to see whether the values being used accurately represent the state of the structure at the time of failure.

Precision & Sensitivity Analysis. Sometimes one or more structural parameters affecting strength are not known with precision. In such cases, it is common to perform sensitivity tests, wherein multiple analyses are performed with uncertain parameters input with their probable high and low extremes.

Determining the Cause of Failure

Analysis of Competing Failure Theories. Failure theories are often developed based on prior experience with similar failures, although the team members should always be open-minded as to the causes or combinations of causes that have never before been experienced. As the investigation advances, facts are collected and failure hypotheses are either substantiated or disproved and dropped. New hypotheses may emerge. In a straightforward investigation, all hypotheses will be eliminated but one (*i.e.*, in only one circumstance do the actions on the structure meet or exceed its predicted capacity). Often, however, the results are not so straightforward and the investigation concludes that different causes are more or less probable. If the estimated loads acting on the structure at the time of failure greatly exceed the predicted capacity, there may be something wrong with the analysis.

Closing the Loop. After the potential failure causes are narrowed to one or a few, reexamine all the evidence to determine if it does or does not support the presumed cause(s). In particular, the evidence regarding the initiation and sequence of the failure should agree with the load-and-resistance analysis.

Reports

The final report is usually the culmination of all of the investigative efforts. It may be the final and only work product the client sees. If it is used as part of a litigation process, it is the basis for the expert's testimony. Well prepared, it may help a client avoid litigation altogether by setting forth the client's engineering case so convincingly that the opposition is compelled to settle. Poorly written, it is a source of unending difficulty for the expert witness and client.

A properly structured report will set forth the factual bases for the analysis as well as a presentation of the facts on which the conclusions will be based. In this respect, the process of writing the report serves as a type of quality check of the investigation, because all facts and opinions must be supported and argued in the text.

For these reasons, it is advisable to devote a significant fraction of the investigative effort to the report. Examples of excellently prepared reports are those of the NBS.[1-3, 31]

Organization. Reports should be organized so that proven facts from a variety of sources are first laid out. Hearsay normally should not be relied on in forming opinions. Where it is necessary to do so through lack of factual information or other reason, such qualification should be clearly stated.

Table 4 provides a general outline for reporting structural investigations. A few suggestions in drafting a report follow:

- The introduction and description of the project should contain information useful for orienting the reader, describing the scope and objective of the investigation, and setting forth the sources of information relied on.
- Field investigation, laboratory tests and calculation results sections set forth factual information obtained from the field program, from laboratory testing, and from calculations. In the testing and calculations sections, the standards employed must be stated clearly.
- All facts collected are reviewed in the discussion section, including statements of what failure hypotheses were explored and an analysis of which hypotheses were proven and disproved and why. The discussion is the first point at which non-factual information is presented. All discussion must be supported by the facts presented in the previous sections.
- Conclusions and recommendations should flow logically from, and be supported entirely by, the discussion.

TABLE 4.
General Report Outline

Letter of Transmittal
Abstract
Table of Contents
  Introduction
  Objective
  Scope
  Background
  Responsible Design & Construction Agencies
  Construction Documents
Description of the Structure (or Project)
Field Investigation
Laboratory Tests
Results of Calculations
Discussion of Field Investigation, Laboratory Tests & Results of Calculations
Conclusions
Recommendations

The entire report must present a convincing and logical argument from the facts to the discussion to the conclusion. The causal relationship between identified deficiencies in design, construction and maintenance must be shown.

Conclusions

Forensic engineering is a specialty distinct from design engineering. The following summarizes the author's experience:

- The investigations of structural failures serve many purposes, most notably to help settle disputes between parties, to diagnose problems so building owners may make repairs, and to help design and construction professionals learn from the failures.
- The activities of the forensic engineer offer, on the one hand, enormous professional challenges. There are few things more difficult than sorting through the wreckage of a structural collapse and pinpointing the cause of the failure. On the other hand, the forensic engineer's work can be disheartening and stressful. No one likes to witness failures of major constructed works, especially when human casualties occur, and the legal process can be fatiguing and hostile.
- Forensic engineers are not prepared for their trade by academic training, and must learn from their own experience and that of others. The synthesis required in structural design is very different from the analysis of structural investigations. Few engineers are both good designers and good investigators.
- A thorough review of case studies of structural failures is invaluable to develop the forensic engineer's expertise and ability to readily form failure hypotheses.
- Structural investigations cannot be reduced to prescribed standards. Each investigation must be tailored to the task at hand. However, there are certain logical processes common to all investigations that help to guide the process.

- Failure investigations involve an iterative process of data collection, formation of failure hypotheses, testing and analyses, and the testing of hypotheses. The goal is to establish the loads and other environmental factors acting on the structure at the time of failure, to establish the resistances of the various critical structural components and, through a process of confirmation or elimination, find the failure cause(s) consistent with evidence regarding the collapse sequence.
- Communication, both verbal and written, of the findings of the investigation are the ultimate product of the work and should receive a substantial fraction of the effort of the investigation.

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The Proactive Engineer: A Vision of Leadership

A well articulated vision and a belief in that view of the future will help restore the profession of engineering to leadership roles in society.

EUGENE J. FASULLO

The future of engineering is a pretty open-ended issue. Everyone has a great idea as to what can be done to reinvigorate the engineering profession and move into the future. However, the idea of "reinvigoration" implies some loss of standing.

Background

Engineering and the role of the engineer in society has changed over the last 35 years. Back in the 1950s and 1960s engineers held a fairly high position of esteem as a profession in the United States. Engineers were master builders, and were viewed by the public as essential to a well functioning society. Engineers held key team positions in the areas of transportation, infrastructure and public works — though perhaps not so much on the national political level in Washington, with the exception of President Carter (who was an engineer). While this lack of representation of the profession among elected and appointed officials has always been a problem; nevertheless, engineers were held in high esteem by the general public.

Since that time, however, there has been a significant erosion of the stature of engineering and in the role that engineers play in society. Some might have a different perception, culminating in different conclusions and a different set of opinions. But the consensus seems to be that this esteem has deteriorated.

If, in fact, there has been a significant erosion of the role of the engineer, what can engineers do about it? There are choices. The most obvious one is that engineers can do nothing. If that's the course of "action," the future typically will be merely an extension of recent history. Unfortunately, that is the way life works. The stature of the profession was high 30 years ago and since then it has dropped. Other professions have taken over many of the aspects of society that engineers once led. There are business management, public administration and construction management roles that did not exist a generation ago. There are a whole host of new professions that are taking a piece of the pie that engineers once had all to themselves.

In fact, it appears that over the years that engineers have abdicated leadership roles. This abdication to others was made for what might seem to have been good reasons. Foremost of these reasons was liability. Engineers do not take any of the responsibility for the construction site because they might be liable. Why is that good advice? Why have engineers been willing to essentially withdraw from the liability controversy, or, for that matter, from any controversy? It seems there is a tacit agreement that engineers should not speak up.

So, there is apparently good reason why engineers have essentially withdrawn from leadership positions. If nothing is done about that in the future, there will be even further erosion of any type of leadership role. Some might even perceive of the profession as almost being irrelevant. Engineering is *not* irrelevant; however, some might *perceive* it as being irrelevant.

Engineers must be engaged strongly — one way or the other — on this issue. Either engineers should be steadfastly sure that everything is fine, or they should feel that it is time to wake up and take a proactive role in redefining the profession. Engineers must make a commitment one way or the other.

Which Way Into the Future?

If someone views the future as an extension of the past — an extension of our own history and personal experience, then it can be said that that person is walking backwards into the future. This approach to the future is similar to driving a car forward while looking in the rear view mirror. Many people live that way, using experience as the basis for tomorrow's actions. In that type of approach, people never really impact or influence the future. The future just happens; it evolves from the past. This concept is important because if engineers do not do anything proactive about their future as a profession, there will be a continuous erosion of the engineer's role and position in society. So, how do engineers (or, for that matter, anyone) go about, in effect, changing the future?

Engineers should think about redefining themselves and not let the present definition of who they are be the picture that is created in the future (which will only result in the further erosion in leadership functions. If engineers want the future to be different, they must look forward into the future, and do something different than was done in the past.

Re-Schooling

One reason why the profession's role has eroded is because of the educational process that engineers undertake. Engineers are not taught to be proactive in engineering school, nor are they taught to take risks. Engineers are taught to consider themselves as occupying a specific technical niche within society, instead of acting as a thread deeply and broadly woven throughout the fabric of society.

The current educational system is designed to produce (almost in assembly-line fashion) specialists who define themselves in a very narrow role not because of bad intent, because of the complexity of what is contained within the specialties. First of all, students are selected on the basis of excellent math and science skills. Other skills are rarely considered for qualifications.

Today, engineering, especially civil engineering, encompasses and requires a much broader range of skills (although, perhaps, it is less so toward the more scientific ends of the profession). Professors are good at teaching students the quantifiable skills of engineering. However, something more is needed to teach the nuances of practicing engineering as a lifestyle. Engineers have to define themselves in a much larger context than math and science. The education process has to take into account a fair share of responsibility for enlarging that perception because that is how engineers present themselves to the world.

Showing Relevance

It is very important that engineers share with each other the concept of what engineering is. Is the profession relevant or not? If it is relevant, are engineers presenting themselves only partially to the world? For example, there is no regular television show about engineering. Other professions (such as law enforcement officers, attorneys, doctors, journalists, etc.) have regular dramatic or comedic shows but there are no regular programs that revolve around engineers on television. Ask children what they think about engineering. Even the children of engineers probably have no concept of what engineers do. There is little done to communicate engineering work to children and, especially, to the world as a whole.

Yet what engineers do is extremely relevant. They deal with the physical world. The profession is emeshed in high technology: computers, airports, port facilities and highways. Engineers constuct, work with and control these things. However, society takes these things for granted because engineers do not share with others what they do. In turn, society takes engineers for granted.

Changing Behavior & Tapping Potential

If engineers share with others what they do, they then have to define what they are to each other and live their lives according to their self definitions. For example, if someone says they are really not introverted, that they are really extroverted, and they then live as if they are extroverted, guess what happens? Engineers, too, can change their image just by changing behavior.

One of the most limiting factors engineers have as human beings is self image. For example, how many people have grown up at home with the image or the message from peers or parents that they are not good athletes. If they have that perception, they will say, "I'm not. . ." Instead, every time that the word *not* is used, listen to what is being said, because there is an awful lot about the perception of one's self in that statement. If someone does not think they are a good athlete, what do they do? They do not participate. The first time the kids in the neighborhood say, "Come on, let's go out and play ball," they will say, "No." They really cannot say yes because they are not very good. They do not want to make fools of themselves in front of friends, so they do not play ball. Naturally, they do not practice and then if they play someday and are thrown a ball, they drop it because they have not practiced and developed skills. What does that do? It only confirms that negative self image, locking the person into a vicious downward cycle.

Engineers might try the following exercise. Every time you say "I am not" to somebody, write down what you say about yourself. Find out how much you define yourself by negatives. All the things that limit life result from all those "I am not" perceptions that are presented to others. Develop, not neglect, limited skills before they become limiting.

Everyone has tremendous potential. The engineering profession has the potential to really contribute great things and it does. But the professional image is that engineers are not outspoken and that they are introverts. Many engineers would rather work alone in front of a computer instead of going to a community board meeting. However, if engineers do not participate, then that initial image gets reinforced.

Redefinition

In order to break these downward cycles of image engineers must redefine themselves. The first step is to publicly say that engineering is not just math and science; it is not just sitting in front of a computer. Engineering is really a very human process; it is an open process that requires social skills. Next, engineers can redefine themselves as being all of those things. Then, the more engineers do those things, the more they will develop those skills and the profession will change its entire image.

Who are engineers? From that question engineers can ask others that will create a clear picture. What do engineers want the profession to be? Given a clean slate, what would engineers design engineering to be? What would it look like? Would engineers be decision makers? One of the key things in this redefinition is recognizing that engineers are decision makers. Do engineers want to participate in public debate about the direction in which society is going? Engineering is defined by the answers to these, and more, questions.

Empowerment

Management and engineering are not separate and mutually exclusive professions: engineering *is* management. Managers can engineer and engineers can manage. Some managers will try to convince engineers that they cannot manage. In the meantime, whose salaries are going up and whose salaries are being held down? Salaries for MBAs do not seem to be capped and yet many engineering firms work on contracts where principals can't charge more $80.00 an hour. If an engineer wants to charge $300.00 an hour, the client does not have to accept it. But why should engineering salaries be artificially capped? Again, it goes back to the view of who engineers are and what role the profession plays. Many clients and other professionals view engineers as just another set of hired hands.

For many engineers, trying to change contracts to eliminate clauses that are really nonsupportive of getting the work done usually elicits the reaction: "What? We cannot do that because we have to get approval from the general counsel." These engineers believe themselves to be totally without power, even if they know what they were asking is completely correct and in the public interest. Engineers must start believing somewhere. For example, the next time an engineer receives a contract that says the principle can bill at only $80.00 an hour, the response should be, "No way." Engineers must start somewhere or the slide will continue.

The Role of Logic

The biggest shortcoming of engineers is to think that the world works out of logic. Engineers feel that there must be a logical premise to everything. Engineers always want the "one" right answer. Although elements of truth may reside in that premise, too many engineers become entrenched in the logical construct, lose sight of the "big" picture and so become completely disempowered. Engineers should spend less time and effort seeking the ultimate logical solution and, instead, formulate a new premise not so much rooted in absolutes. The answer does not have to be perfectly right since all too often there really is no truly right or perfect answer.

Engineers have to change how they approach things and adopt a point of view where they have the power to impact their future. Unfortunately, there is very little absolute truth in the world; instead, truth resides more in how it is perceived. This "program" might not appear to be very logical. Instead of looking for logic, it is better to look at how people truly work and operate (which is often not thoroughly based in logic).

For example, there has been a lot written about what kind of spouse engineers make. The advice columnist Ann Landers has had published many articles about engineers. In all, there are many articles that define an engineer as a spouse. Most of the letters to Ann Landers contain complaints about an engineer spouse not being the greatest marriage partner even though they are good providers, very reliable, very logical, have high integrity and are the last person to cheat on their spouse. So why the complaints? It is because engineers are too logical and seem to be never without some sort of home project. Many engineers feel uncomfortable just talking. Engineers would rather talk about how to design a cable stayed bridge. Or they retreat into some sort of activity or project, prefering that life be a series of problems to be solved by the most logical means. That is what engineers perceive the profession to be about, and they are extremely good at it. It really seems to be a professional obsession, this necessity to have a project, something to focus on — to crave definition, structure. Why this need for structure? Because they are *engineers*. The educational process starts engineers on this track and never lets them off.

Speaking Out

Our society is mining our infrastructure. Engineers see that every day and yet say nothing. Who is going to be the advocate for infrastructure reconstruction if engineers do not consider that to be their intrinsic responsibility? Politicians will be there only when a new facility is opened. They will not worry whether a bridge is rusting and, in five years, there is a possibility that it may fall down. Politicians could care less: they will not be in office five years later.

Politicians are short-term thinkers; they are not going to speak up about long-term effects. Bridges do not say, "Please help. In five years I'm going to fall down." Who is going to tell that to the public if not for the engineer? But in our current climate, the engineer will be criticized for doing so — not a great incentive to speak up.

Engineers have good reasons for not speaking up: their educational process teaches them to be quiet. Engineers are taught in class not to speak unless they have the right answer. Therefore, it is not surprising that engineers will be silent at public hearings (where there is no right or wrong answer).

Engineers need to look at their behavior, especially at how they behave in a group environment. The fact that most of these issues are not black and white motivates behavior. Perhaps the engineer feels about 95 percent right, but is not willing to speak up because that 5 percent is still missing. Anybody else speaking will know probably 5 percent, but they are willing to get up and speak anyways. For example, lawyers will get up and speak about anything and anytime. They will take any position because they are taught to do so in school. One day a lawyer defends one side, the next day the lawyer is on the other side, having to play an equally and effective dynamic role. In one sense, it is not about being right. It is about being an advocate, a voice. Therefore, it does not seem to be such a surprise that engineers are silent.

A Vision of the Future

Engineers should create a vision of the future for themselves and not worry about how to get there, or even if that vision makes any sense. There really is no next step or the right step, or the right answer, only another question: do engineers agree that they have to do something different? Each engineer may reach that vision in different way, but there has to be agreement on that goal. The next step will present itself to each and every engineer just by living life, and by living committed to that goal.

Engineers have to think in earnest about the future and have to share that vision of the future with each other. No individual engineer has the complete picture of the future. This profession will not affect any change anything unless it does it collectively — by sharing, by meeting together. Discussions on this issue have been rare. Frankly, there has to be more dialogue. Without sufficient communication of hopes, dreams and concerns, engineers will not come together an achieve an agreement about this issue. This communication has to be on the grassroots level, not on some wonderful and grandiose conceptual view of what to do next.

In the real world — the world engineers inhabit — engineering is extremely open-ended. It is creative. It involves risk-taking. It occurs in a highly entrepreneurial environment. Think about those bridges that are built and other vast public works. These projects are not the products of a "nerdish" profession. Such a viewpoint comes from a view of engineering created from a definition of the profession that does not truly reflect the way things are.

There is no single way of getting to the vision of the future. Everyone in their own life can get there but in a different way. Large firms have different issues to deal with, the same in a small firm, and so on. The answer is what each and every individual engineer is committed to do.

Living Differently

When discussion of the direction of the profession occurs, engineers are rededicating themselves. Becoming affected by this discussion, they begin to participate. They start living their lives differently.

Conceptually, looking at how people live and evolve and the way they create their future, engineers have two choices:

- Either someone can continue looking at the future by looking backwards (a way most of us live); or,
- Looking forwards by proactively redefining the future.

It is more difficult to turn around and say, "I'm going to create the future." However, the simple act of verbalizing that dream of the future is the key to open a very powerful self image. This might sound simple-minded, but it is a very powerful principle — to say something about yourself and put it into action. The problem with looking backwards is that the results are, at best, going to be more of the same, or, at the worse, going to result in even more erosion. The future is undefined. Engineers now have an opportunity to define that future. Engineers need to speak out, to participate, to realize the power inherent in the profession — both collectively and individually — and use it to take every opportunity to bring others into the new vision of who engineers are.

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