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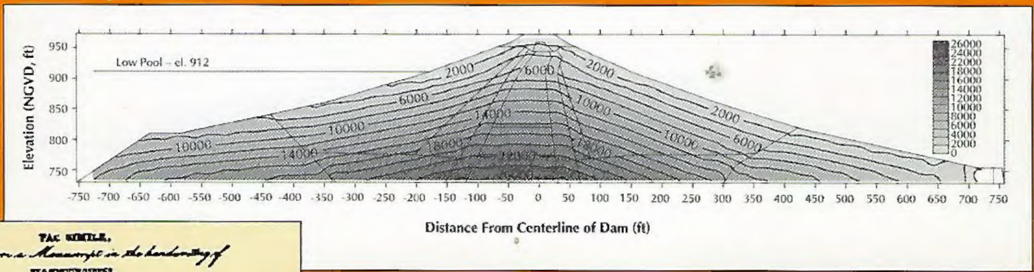
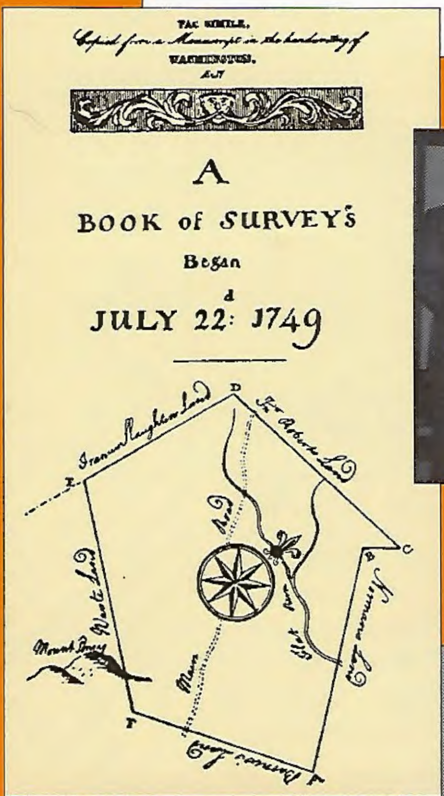
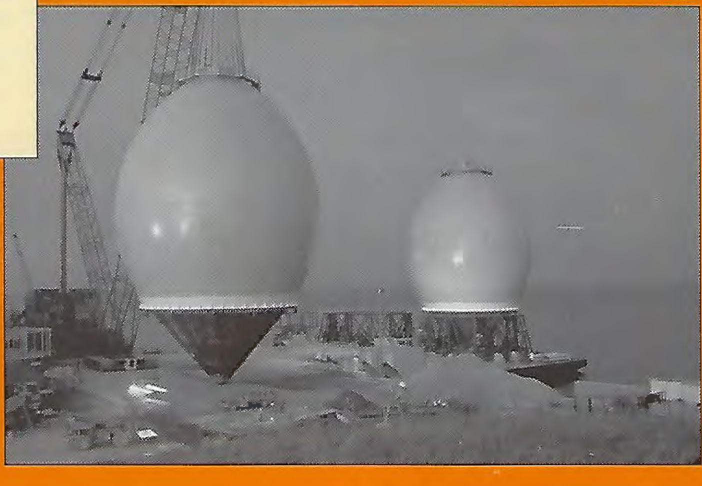
Seismic Response Analysis of a Hydraulic Fill Dam





Pioneers in Soil Mechanics

Facilities Planning for the Boston Harbor Cleanup



George Washington, Engineer

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Editorial, Circulation & Sales Office:

Civil Engineering Practice
Boston Society of Civil Engineers
Section/ASCE
The Engineering Center
One Walnut St.
Boston, MA 02108

Phone: (617) 227-5551
Fax: (617) 227-6783
E-Mail: CEP@quale.com
Web Site:
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A Tradition of Excellence

Back in August I received a phone call from Allen Marr who was working with an ASCE committee of eminent experts in geotechnical engineering. This group was in the process of selecting papers that had been published in the United States that have contributed significantly to the field of geotechnical engineering. The committee deliberations led to the selection of 78 papers, seven of which had appeared in BSCE publications, and Allen was seeking the permission of BSCES to publish these papers as part of an ASCE special publication entitled *A History of Progress: Selected U.S. Papers in Geotechnical Engineering,* which appeared in November 2002. Six of these papers were published in the *Journal of the Boston Society of Civil Engineers* and were authored by such pioneers as Karl Terzaghi and Arthur Casagrande. When I look back at the compendium of engineering work reported in *Civil Engineering Practice* and its predecessor, *Journal of the Boston Society of Civil Engineers,* I can't but feel a sense of pride and responsibility in carrying this tradition of excellence. We at the editorial board encourage all of our friends and fellow civil engineers to help us by supporting the journal. This support can be in the form of submitting papers, helping in the paper review process or considering the journal for advertising your business.

In the spirit of this sense of tradition and engineering heritage, we have selected an article that first appeared in the old *Journal of the Boston Society of Civil Engineers* in 1932 for our current issue. "George Washington, Engineer" by B. Edward Grossman looked at some aspects of our first president's life that were less explored, certainly at the time of publication of this article. The article highlights Washington's accomplishments as a land surveyor, agricultural engineer and land developer by drawing on many sources, including Washington's own notes. It is a fascinating account of our first president's engineering knowledge and talents. It is also an important historical document since it gives us a glimpse into engineering practice as it was conducted more than two hundred years ago. The article, "Pioneers in Soil Mechanics: The Harvard/MIT Heritage," also shows us how the science and practice of geotechnical engineering developed in the last century. Compiled and edited by Anni Autio and Michael McCaffrey from a presentation at the 1998 ASCE Convention in Boston by five key figures in the development of soil mechanics – Harl Aldrich, Ronald Hirschfeld, Ralph Peck, Steve Poulos and Robert Whitman – the article gives us first-hand accounts of how this new field grew in our own backyard here in the Boston area. I hope that you will enjoy reading these articles, as well as the other articles included in this issue, and consider supporting your journal in any way you can.

Ali Touran

Ali Touran
Chair, Editorial Board, *Civil Engineering Practice*

Seismic Response Analysis of Cobble Mountain Reservoir Dam

Six finite element programs, each appropriate to a particular phase of analysis, were used instead of a single large program to predict dam behavior during an earthquake.

ALFREDO URZUA, JOHN T. CHRISTIAN, WILLIAM H. HOVER, IVAN A. HEE & STANLEY M. BEMBEN

The Cobble Mountain Reservoir Dam, located in Russell, Massachusetts, impounds the city of Springfield's primary water supply (see Figure 1). Constructed from 1929 to 1932 by hydraulic filling methods, it has a crest length of 730 feet and a maximum height of about 260 feet. The dam is a large, high-hazard structure.[1,2] It is the highest hydraulic fill dam in the world and is the highest dam in Massachusetts. Two consulting engineers were engaged as project engineers by the Springfield Water and Sewer Commission (SWSC) to evaluate the seismic stability of the dam. One was designated as the leader and all services by all of the consultants were under the lead consulting engineer's direction on behalf of the SWSC. When on-going pseudo-static analyses indicated that the dam was likely to be deemed safe, the leader promulgated a finite element dynamic analysis by a qualified consulting engineering firm. That analysis is the basis of this presentation. All contributions were included and evaluated in the project report and in a contracted version.[3,4]

The present analysis concerns the dynamic response of the embankment, evaluation of liquefaction potential and estimation of permanent deformations. Others undertook field investigations, laboratory tests, seismic hazard calculations and stability analyses. Because no available computer program can handle all the steps in the analysis, six finite element programs were used, each appropriate to one phase of the analysis. The same mesh was used for all the finite element programs. Short, special-purpose programs generated intermediate results and modified input between programs. Where the standard procedures for evaluating soil performance depend on published graphs, equivalent analytical interpolation routines were developed. Colored contours and plots of deformations made the results readily understandable. This

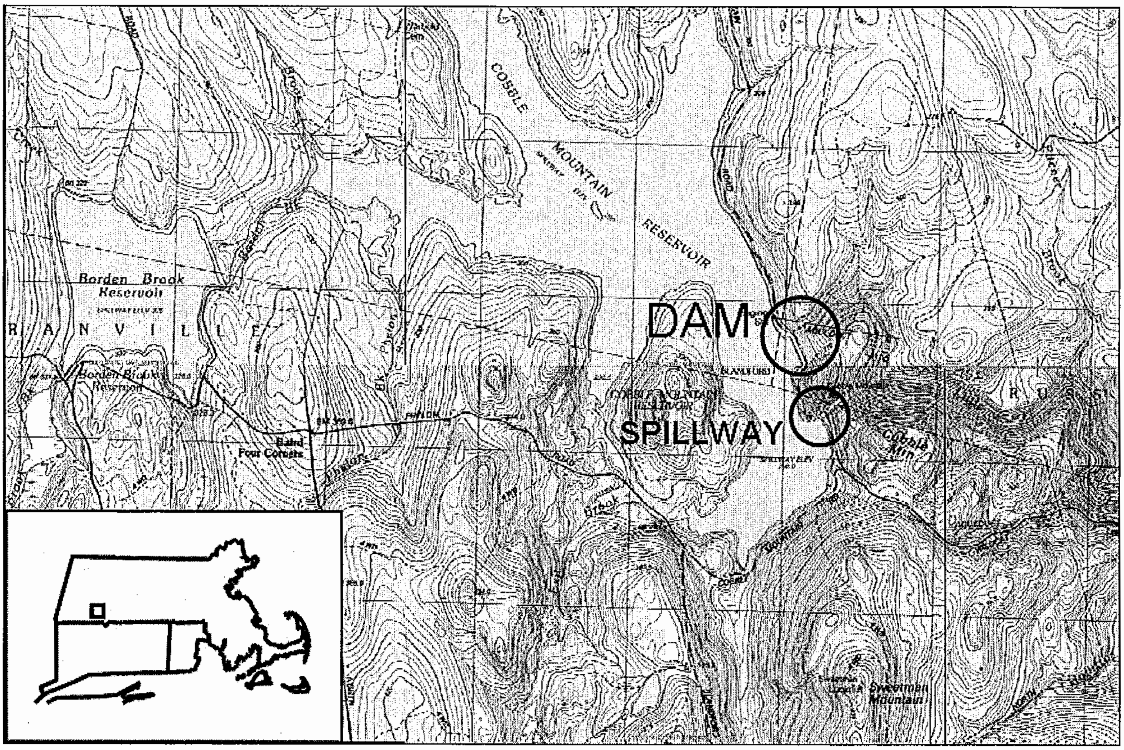

FIGURE 1. Location of Cobble Mountain Dam.

approach obviated the need to develop and debug a large computer program and provided abundant intermediate input invaluable in guiding the analysis.

Initial Conditions & Input Motions

Cross-Section & Material Properties. Figure 2 shows the central maximum cross-section of the dam. The cross-section was divided into the ten materials identified in the figure on the basis of:

- Logs of field explorations conducted in 1999;[3]
- An earlier boring program described by Roald Haested;[5]
- Laboratory and field tests during dam construction;[3] and,
- Laboratory testing with unit weights and other parameters developed and reported by Bemben and Zoino.[3]

The figure shows interpretations of the unit weight and effective friction angle for each material and also includes outlines of the finite element mesh used in the static and dynamic stress analyses. The seepage analyses used the same initial mesh, but some of the material identifications were changed. Figure 3 shows the values of the hydraulic conductivity for the various materials inferred from the results of grain size and permeability tests taken during construction and current explorations. In some later refined analyses, an eleventh material was added to represent rockfill on the upstream slope.

In addition to the properties identified on Figures 2 and 3, the analyses required that the masses and stiffnesses of the materials be established, and the liquefaction analyses required a measure of resistance of the embankment soils to liquefaction – in this case the standard penetration test N values. The masses were computed directly from the unit weights.

The stiffnesses of the various embankment materials were expressed in terms of the shear moduli, which were evaluated by a multi-step procedure. First, for each section of the dam,

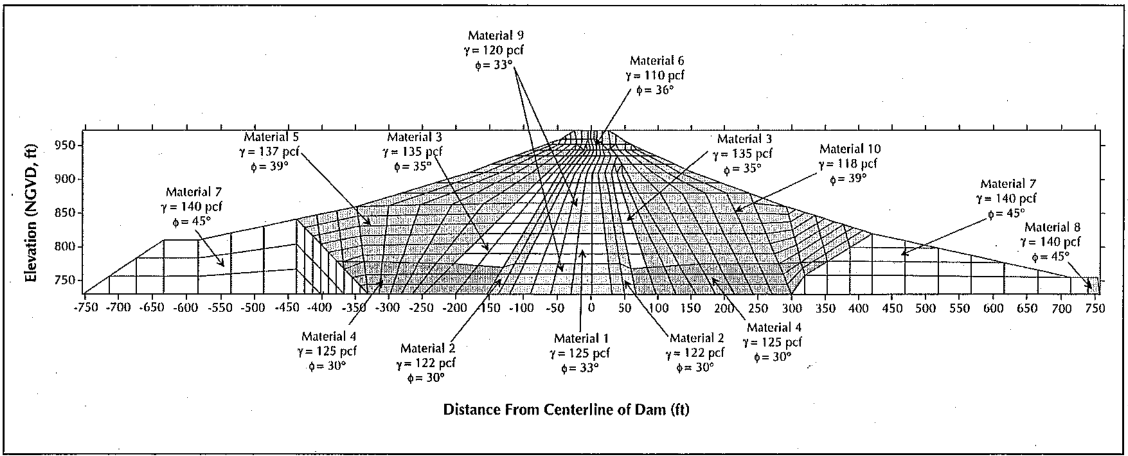

FIGURE 2. Cobble Mountain Reservoir Dam cross-section showing materials and finite element mesh for stress analyses.

the void ratio, e, was computed from the value of the unit weight, using a specific gravity of solids, G, of 2.7. The unit weight of water was taken to be 62.4 pounds per cubic foot (pcf). Next, the vertical effective stresses were estimated from the weight of overburden above the point of interest minus the pressure of water computed from the flow net described below. Values of Poisson's ratios, ν, were estimated from the results of triaxial tests, and the horizontal effective stresses were computed as the products of the vertical effective stresses and $\nu/(1-\nu)$. Poisson's ratios ranged from 0.33 for the transition zone and the bottom layer upstream of the transition zone (Materials 2 and 4) to 0.23 for the rockfill zone (Materials 7 and 8). One-third of the sum of the vertical and two horizontal effective stresses gave the octahedral stress, $\bar{\sigma}_o$. Hardin and Black gave formulas for the shear modulus of sands and clays in terms of the void ratio and the octahedral stress.[6] Seed and Idriss gave formulas for the shear modulus of gravels in terms of the octahedral stress.[7] These values are for small strain deformations, also called the "initial" modulus values. Adjusting the parameters in these formulas so that the results agreed with the available measured profiles of shear wave velocity in the field gave the following formulas for the shear moduli at small strains:[8]

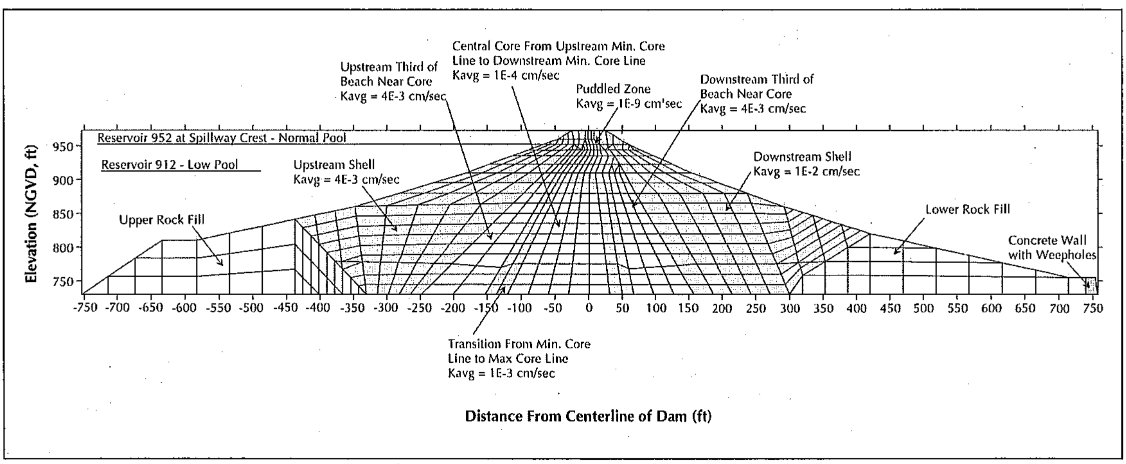

FIGURE 3. Cobble Mountain Reservoir Dam cross-section showing finite element mesh for flow analyses

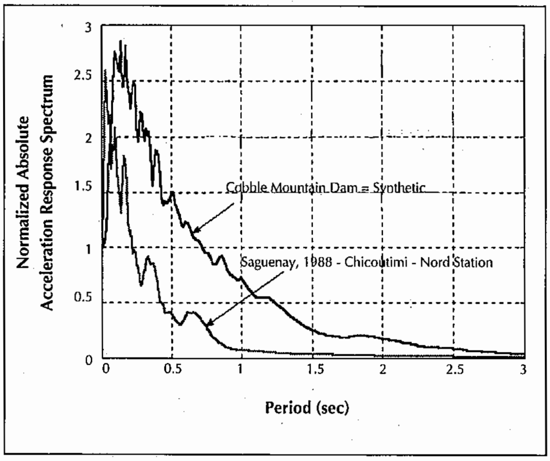

FIGURE 4. Design response spectra.

$$G = (467)\ ((2.97\text{-}e)^2/(1+e))\ \sqrt{\bar{\sigma}_o} \quad \textbf{(1)}$$
$$G = (3{,}795)\ \sqrt{\bar{\sigma}_o} \quad \textbf{(2)}$$
$$G = (998)\ ((2.17\text{-}e)^2/(1+e))\ \sqrt{\bar{\sigma}_o} \quad \textbf{(3)}$$

Equation 1 applies to Materials 1 and 6; Equation 2 applies to Material 7; and Equation 3 to the other materials. Both G and $\bar{\sigma}_o$ are in kips per square foot (KSF). These formulas were applied element by element to obtain an initial estimate of the distribution of shear moduli.

Conservative estimates of the standard penetration test N values were at or near the lowest values found in current explorations (correlated with energy measurements by Heller and Johnsen, and the corrected values by Bemben-Zoino study[3]). For the gravels in Material 7, N was taken to be 25. For the core Materials 1 and 9, N was taken to be 8, which is increased from 7 because the tests had higher than usual energy transmission. For Material 2, N was taken to be 12. For all the other materials an N value of 15 was used.

Earthquake Records. A probabilistic seismic hazard analysis was conducted in 2000 and yielded two possible design earthquakes for incorporation into the seismic analysis.[9] One was a synthetic record developed conservatively for this project, called the "Cobble Mountain Synthetic Earthquake." The other was one of the actual records of the 1988 magnitude 5.8 Saguenay earthquake at Chicoutimi-Nord Station, Québec. Each of these earthquakes were scaled to peak base accelerations (PBA) of 0.12 g and 0.16 g to reflect different levels of earthquake magnitudes, corresponding to recurrence intervals of about 6,000 years and 10,000 years, respectively. The Chicoutimi-Nord earthquake was also scaled to 0.204 g to represent an event similar to that considered by others for the Knightville Dam.[10] The project engineers selected the synthetic earthquake with a PBA of 0.16 g and the actual record earthquake with a PBA of 0.204 g as the two design cases. (The Knightville Dam is about 12 miles to the north-northeast of the Cobble Mountain Dam.) The shapes of the acceleration spectra for 5 percent damping for the records normalized to 1.00 g are displayed in Figure 4.

Initial Effective Stress Conditions. To calculate the *in situ* initial effective stress conditions, the total vertical stresses were first computed with the finite element program SIGMA/W using total unit weights.[11] Figure 5 shows the contours of vertical total stress for the reservoir at full pool (spillway crest at elevation 952 — datum is National Geodetic Vertical Datum [NGVD]), and Figure 6 shows the contours for the reservoir at low pool (ele-

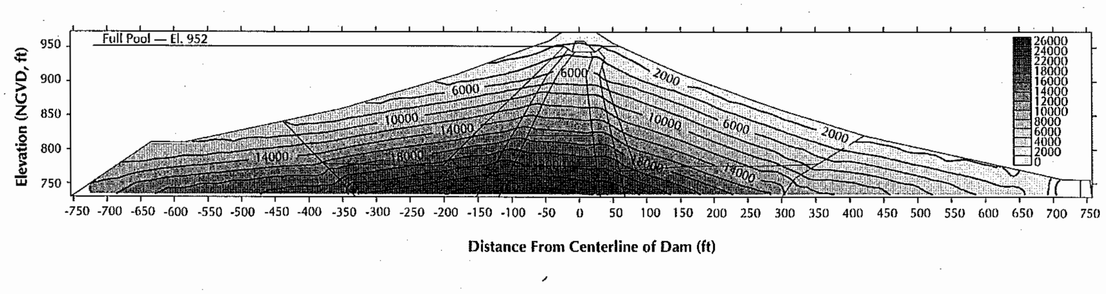

FIGURE 5. Initial total vertical stresses at full pool.

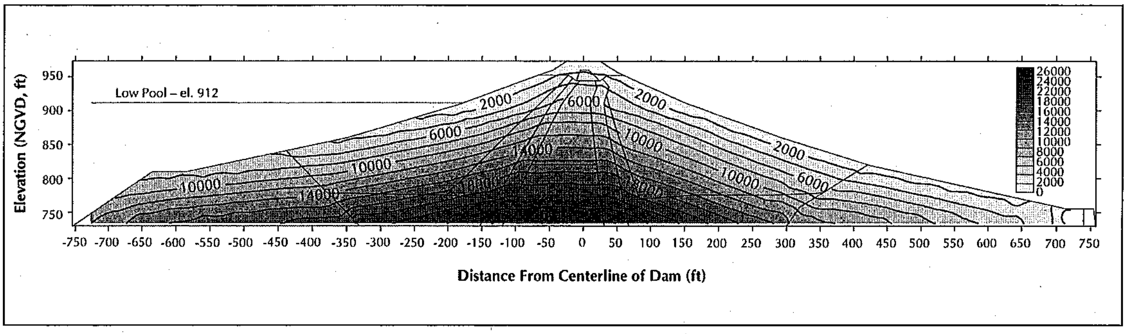

FIGURE 6. Initial total vertical stresses at low pool.

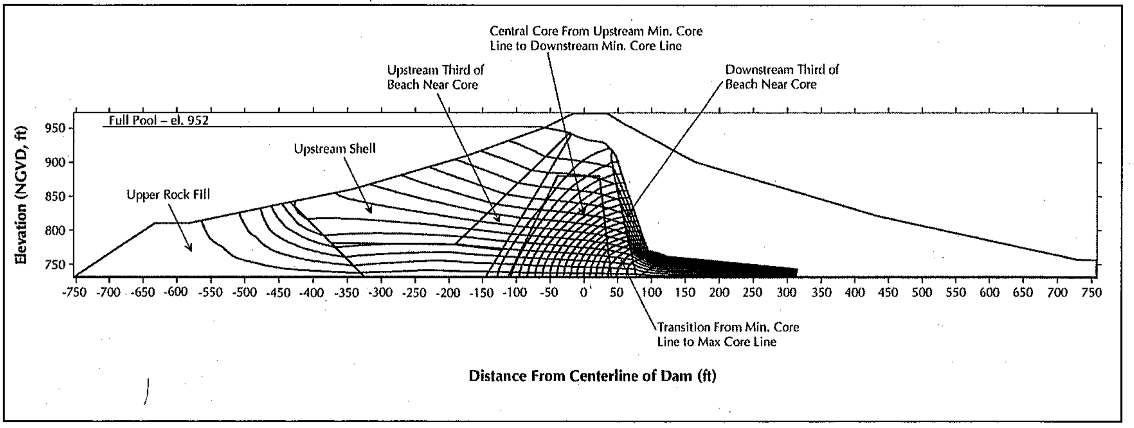

FIGURE 7. Flow net at full pool.

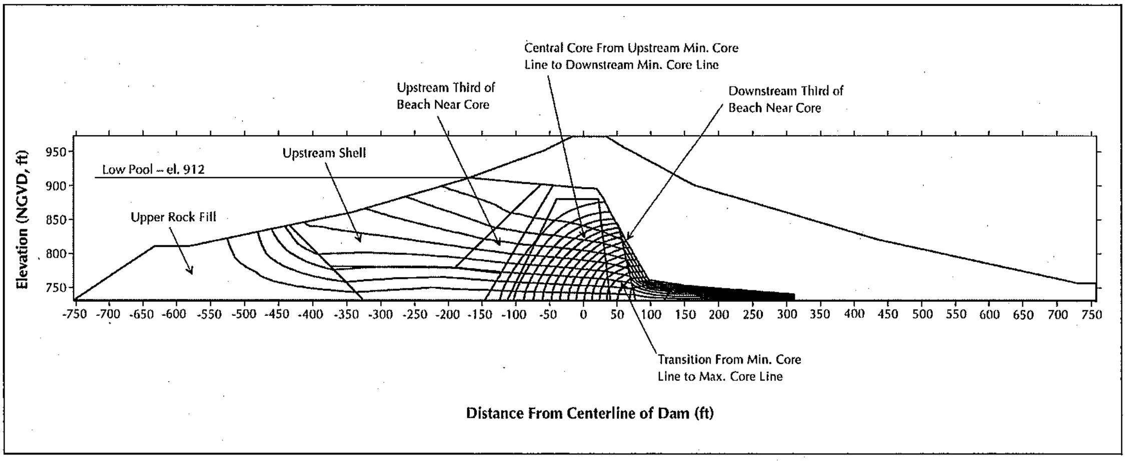

FIGURE 8. Flow net at low pool.

vation 912, or 40 feet lower than full pool). The seepage regime was evaluated using two finite element programs: SEEP/W[12] and a proprietary program that could plot the full flow net (seepage flow lines as well as the equipotentials) using Christian's method.[13] Seepage was evaluated for the reservoir at elevation 952 feet (full pool) and at elevation 912 feet (low pool). Figures 7 and 8 show the flow nets for the two conditions. Finally, the pore pressures found from the SEEP/W analyses were subtracted from the total vertical stresses to

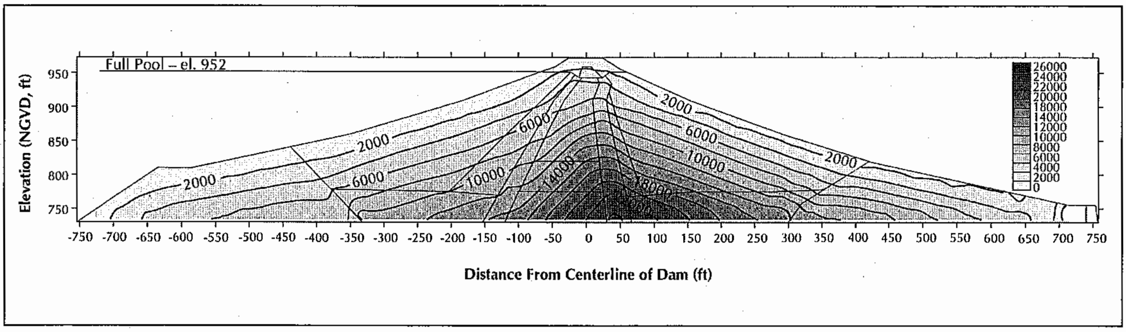

FIGURE 9. Initial effective vertical stresses at full pool.

give the effective vertical stresses plotted in Figures 9 and 10.

Response Analysis Methodology

The response of an embankment to seismic shaking is a complicated process involving many phenomena. In an ideal world there would be one or two computer systems that could accommodate the full range of behavior and geometry, but that is not now the case. Furthermore, the elaborate systems that do exist are relatively inflexible and hard to adapt to specific conditions. Therefore, it was decided to proceed with several proven analytical tools and to do so in a way that intermediate results could be conveniently transmitted from one finite element program to another. An essential component of this approach was the decision to maintain one finite element mesh.

Two-Dimensional Analysis. Two computer programs were selected to perform the dynamic analysis: QUAD-4M and FLUSH. The QUAD-4M model works in the time domain — *i.e.*, the effects of the earthquake motion input at the bedrock foundations at the base of the dam are calculated one time step at a time throughout the record.[14] The FLUSH model works in the frequency domain — *i.e.*, it first performs a fast Fourier transform on the earthquake record to obtain Fourier amplitudes at different frequencies, solves the response at each frequency and then transforms the results back into the time domain.[15] Both programs evaluate the maximum shear stress in each element and use 65 percent of these values to calculate the appropriate strain-dependent values of modulus and damping for each element. Furthermore, since both models were expected to produce generally similar results, using two models in some ways helped provide a check of accuracy input. The present analysis employed the modulus and damping curves developed by Vucetic and Dobry.[16] The results of the analyses were values of horizontal shear strains and shear stresses at the centroid of each finite element in the 522-element mesh. The models also yielded internal accelerations and peak volumetric strains within the dam as a result of the base excitation. QUAD-4M consistently gave slightly higher responses than

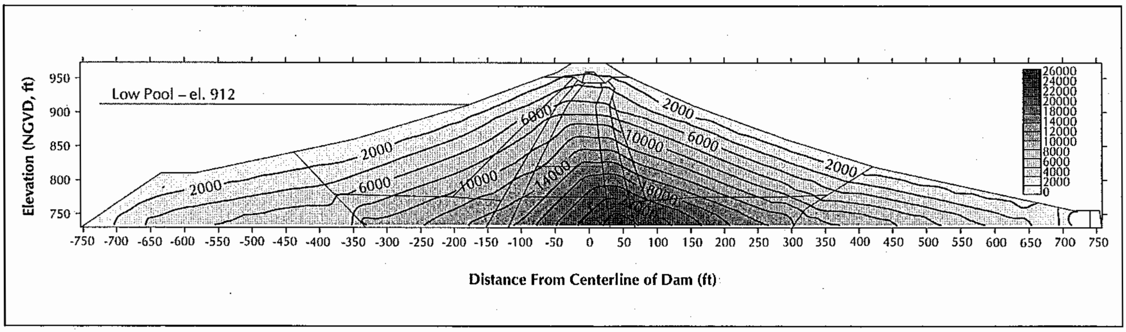

FIGURE 10. Initial effective vertical stresses at low pool.

FLUSH for the 0.12 g and 0.16 g earthquakes. Therefore, only QUAD-4M was used for the later analyses at 0.204 g.

Pseudo-Three-Dimensional Analyses. The two-dimensional analyses assume that the dam is a prism extending infinitely perpendicular to the plane of the cross-section (*i.e.*, along the long axis of the dam). In fact, the length of the dam between abutments is less than the distance from toe to toe at the maximum section. The ratio of length to height of the longitudinal distance or crest length, L, to the maximum height, H, is 3 for the Cobble Mountain Dam. Makdisi *et al.* proposed a procedure for making the necessary corrections for three-dimensional effects.[17] They reported that, for L/H equal to 3, the ratio of the fundamental frequency under three-dimensional conditions to that computed for two-dimensional conditions is 1.6. This ratio is designated R_f. The iterated two-dimensional final fundamental period given by the QUAD-4M or FLUSH is T_{2D}. Then, the three-dimensional fundamental period T_{3D} is equal to T_{2D} divided by R_f. For a particular response spectrum the spectral acceleration at T_{3D} is Sa_{3D}. The spectral acceleration at T_{2D} is Sa_{2D}. Then R_{Sa} is equal to Sa_{3D} divided by Sa_{2D} (the ratio of the three-dimensional to the two-dimensional spectral acceleration) and R_{Sd} is equal to R_{Sa} divided by the square of R_f (the ratio of the spectral displacements). A simple program was written to read the output of the two-dimensional analyses and compute this ratio for each element. The iterated fundamental period computed in the two-dimensional analyses varied with the level of shaking, the computer program that was used and the time history, but values generally fell between 1.1 and 1.3 seconds.

For a particular element from the QUAD-4M or FLUSH results, the two-dimensional effective horizontal shear strain is $\gamma_{xy,eff}$ (65 percent of the maximum value). The new effective shear strain, $\gamma_{xy,eff,\ new}$, is equal to $\gamma_{xy,eff}$ times R_{Sd}. For $\gamma_{xy,eff,\ new}$, the Dobry-Vucetic curves give a new value of shear modulus, G_{new}. The new value of the effective cyclic shear stress, $\tau_{eff,\ new}$, is equal to G_{new} times $\gamma_{xy,eff,\ new}$. The new value of the cyclic shear stress, $\tau_{eff\ new}$, can then be used in the calculations of settlement and factors of safety against liquefaction.

Liquefaction Analysis. Liquefaction analysis compares the horizontal shear stresses generated by the earthquake with the resistance available to prevent liquefaction. The shear stresses are expressed in terms of a cyclic stress ratio (CSR), and the resistance in terms of a cyclic resistance ratio (CRR). The procedures used here are those proposed by the 1996 National Center for Earthquake Engineering (NCEER) and 1998 NCEER/National Science Foundation Workshops, which represent the latest consensus on the state of practice.[18]

The CSR is equal to 65 percent of the ratio of the peak horizontal shear stress generated by the earthquake to the initial vertical effective stress:

$$CSR = 0.65 \bullet \tau_{peak}/\bar{\sigma}_{v,init} \qquad (4)$$

The factor of 0.65 represents an averaging over the time history. The CRR is found from a plot of CRR versus the standard penetration test N value corrected for 60 percent energy efficiency and for a vertical effective stress of 1 ton per square foot (or, $(N_1)_{60}$). The plot is found in Youd *et al.*, but it is based on a series of publications by Seed and his co-workers dating back to the 1970s.[18] Except as noted above, the N values found in the field exploration program generally represent 60 percent energy efficiency. The correction for the vertical effective stress is achieved by multiplying the N value by C_N (which is equal to $(2{,}000/\sigma_{v,init})^{1/2}$), where the stresses are in psf. It is also necessary to correct for a fines content larger than 5 percent. This correction is done using the formula:

$$(N_1)_{60,\ corrected} = \alpha + \beta \bullet (N_1)_{60,\ uncorrected} \qquad (5)$$

This correction is necessary only for the material in the core, where α is equal to 5 and β is equal to 1.2.

The factor of safety against liquefaction is then computed from:

$$FS = (CRR/CSR) \bullet MSF \bullet K_\sigma \bullet K_\alpha \qquad (6)$$

MSF is a magnitude-scaling factor to account for the fact that the magnitude at which the empirical factors were calibrated is 7.5. In the present case, with the three levels of acceleration, the MSF was 1.75, 1.7 and 1.5 for the 0.12 g, 0.16 g and 0.204 g earthquakes, respectively. K_σ varies between 1.7 and 0.5 as a function of the overburden stress according to charts presented by Youd *et al.*[18] K_α is difficult to estimate; it was assumed conservatively to be 1.0.

Estimated Strains & Settlement. The output from both the QUAD-4M and FLUSH programs includes peak values of shear strain during the earthquake. For soils above the phreatic surface, Tokimatsu and Seed gave relations between the volumetric strain, the peak shear strain and N value.[19] For each element above the phreatic surface, the peak shear strain computed from the dynamic finite element analysis and the N value at that point were entered into the Tokimatsu and Seed relations to yield the volumetric strain. For saturated soils beneath the phreatic surface, Ishihara and Yoshimine gave relations for the volumetric strain as a function of the factor of safety against liquefaction and the N value.[20] (The relation is in the form of a chart that is also found in Ishihara's book.[21]) For each element below the phreatic surface, the factor of safety against liquefaction and the N value were entered into the Ishihara and Yoshimine relation to obtain the volumetric strain. The results of the Tokimatsu and Seed and the Ishihara and Yoshimine computations are unconstrained volumetric strains in the sense that they do not account for the restraining effect of adjacent elements.

Both the Tokimatsu and Seed and the Ishihara and Yoshimine relations are in the form of charts, which cannot be used directly in a computerized, element-by-element analysis. Therefore, second-order regression analyses were run using the points in the charts to obtain analytical forms appropriate for interpolation. The Ishihara and Yoshimine chart had to be divided into three sections to obtain adequate resolution.

The unconstrained volumetric strains were then used as input conditions to a general-purpose finite element program, PC-FEAP.[22] This program redistributed the displacements to restore continuity, yielding a deformed continuous mesh and a settlement profile of the top of the dam along the maximum section.

Major Results

The dam was analyzed in order of increasing level of peak base acceleration at the top of bedrock – 0.12 g, 0.16 g and 0.204 g. The results include contours of factor of safety against liquefaction, deformed meshes showing the effect of volume change following the earthquake and estimated settlement profiles for the top surface of the dam along the maximum section. Each of these three levels of shaking describes results that include the effects of the three-dimensional corrections. However, in order to demonstrate the relative contributions of various parameters, the results of the 0.12 g peak base acceleration includes a description of the two-dimensional results as well.

Peak Base Acceleration – 0.12 g. Figures 11 through 14 display the contours of the factor of safety against liquefaction for the reservoir at full pool when it is shaken by earthquakes with a peak base acceleration of 0.12 g in the bedrock surface beneath the dam. The four figures include all combinations of two time histories (Cobble Mountain synthetic record and the Chicoutimi-Nord record) and two methods of analysis (QUAD-4M and FLUSH). The results are for two-dimensional analyses with no corrections for the upstream slope rockfill zone effects. The results demonstrate that the most severe of the four cases is that of the Cobble Mountain synthetic record analyzed with QUAD-4M. The minimum value of the factor of safety was 1.25, located within the 1.5 contour in Figures 11 and 12.

The deformed mesh in Figure 15 shows the shape of the dam after the volumetric strains induced by the 0.12 g earthquake shaking have been accounted for. The deformations are exaggerated 25-fold. These results are from a two-dimensional analysis using QUAD-4M and the Cobble Mountain synthetic record.

For the case of reservoir at the low pool level, Figures 16 through 19 show the corresponding contours of the factors of safety against liquefaction. Figure 20 shows the deformed mesh. Again, the deformations are exaggerated by a factor of 25, and these results are also for two-dimensional analyses.

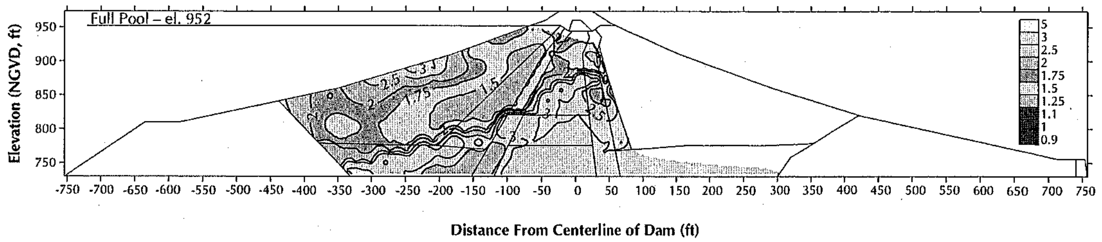

FIGURE 11. Factors of safety against liquefaction, Cobble Mountain synthetic earthquake, QUAD-4M analysis, peak base acceleration 0.12 g, full pool, two-dimensional analysis.

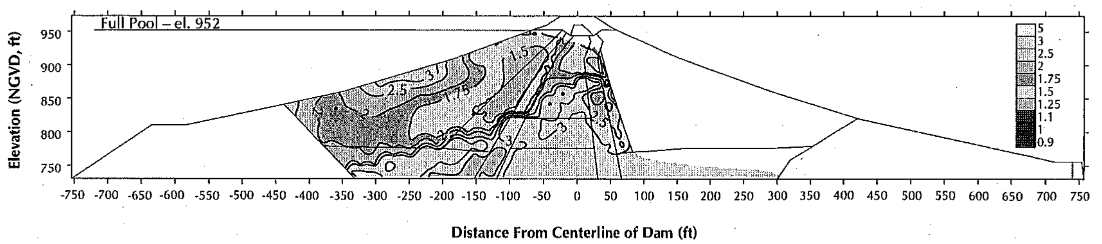

FIGURE 12. Factors of safety against liquefaction, Cobble Mountain synthetic earthquake, FLUSH analysis, peak base acceleration 0.12 g, full pool, two-dimensional analysis.

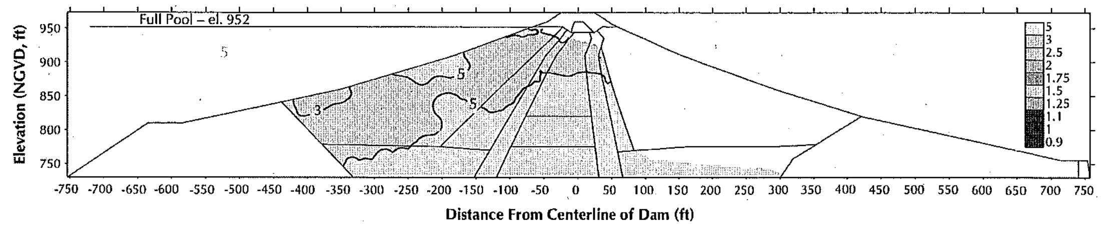

FIGURE 13. Factors of safety against liquefaction, Chicoutimi-Nord record, QUAD-4M analysis, peak base acceleration 0.12 g, full pool, two-dimensional analysis.

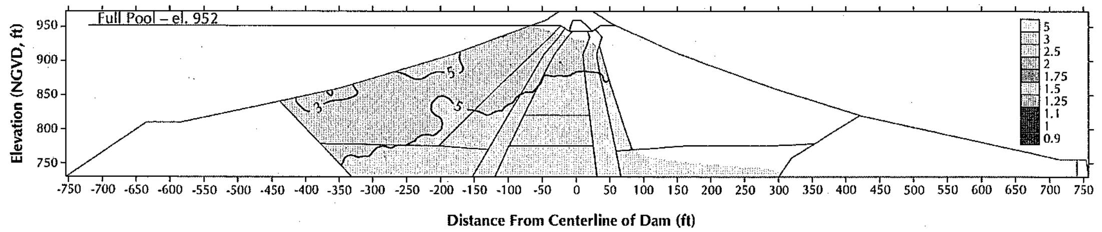

FIGURE 14. Factors of safety against liquefaction, Chicoutimi-Nord record, FLUSH analysis, peak base acceleration 0.12 g, full pool, two-dimensional analysis.

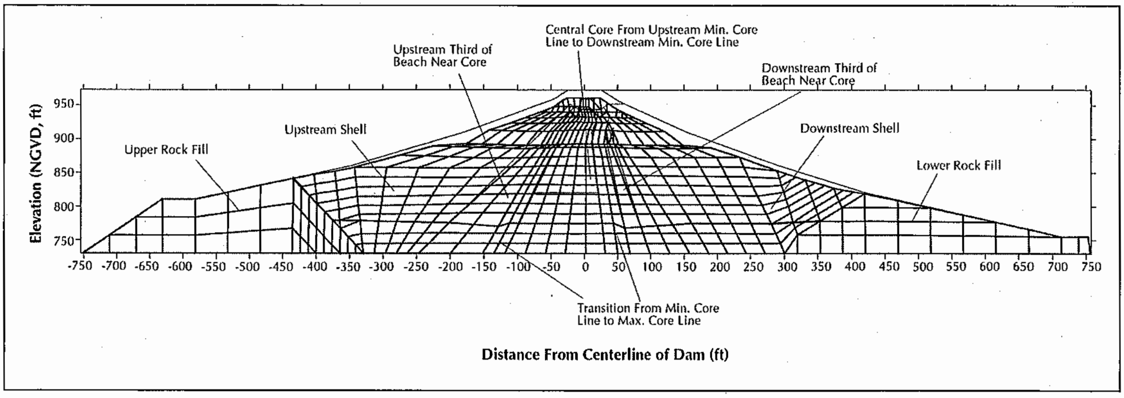

FIGURE 15. Deformed mesh (25-fold exaggeration), Cobble Mountain synthetic earthquake, QUAD-4M analysis, peak base acceleration 0.12 g, full pool, two-dimensional analysis.

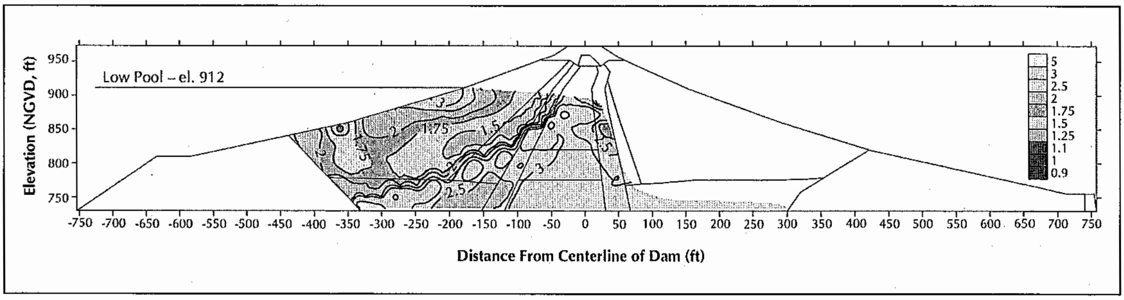

FIGURE 16. Factors of safety against liquefaction, Cobble Mountain synthetic earthquake, QUAD-4M analysis, peak base acceleration 0.12 g, low pool, two-dimensional analysis.

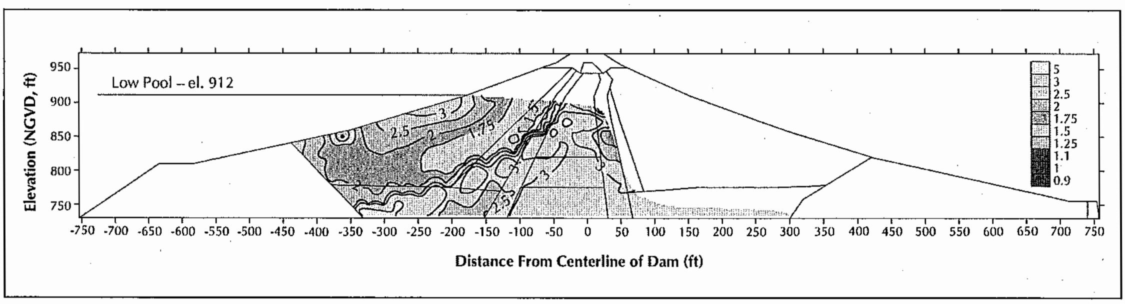

FIGURE 17. Factors of safety against liquefaction, Cobble Mountain synthetic earthquake, FLUSH analysis, peak base acceleration 0.12 g, low pool, two-dimensional analysis.

Figure 21 is a plot of the estimated final settlement of the top of the dam in the two-dimensional analyses. Six cases are plotted: full and low pool for 0.12 g, and full and low pool for 0.16 g with and without upstream rockfill modeled. In all cases, the results are for the Cobble Mountain synthetic record and the QUAD-4M program. When the three-dimensional corrections are made for the case of full pool, the contours of factor of safety against liquefaction become those that are shown in Figure 22. This figure uses the results of QUAD-4M analysis with the Cobble Mountain synthetic record normalized to 0.12 g. The factors of safety for the Chicoutimi-Nord record at 0.12 g are contoured in Figure 23. The deformed mesh, with deformations exaggerated by a factor of 25, is plotted in Figure 24 for the Cobble Mountain synthetic record and in Figure 25 for the Chicoutimi-

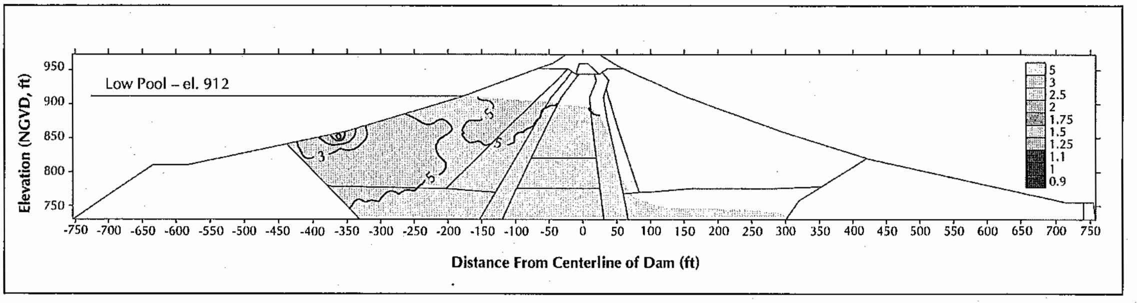

FIGURE 18. Factors of safety against liquefaction, Chicoutimi-Nord record, QUAD-4M analysis, peak base acceleration 0.12 g, low pool, two-dimensional analysis.

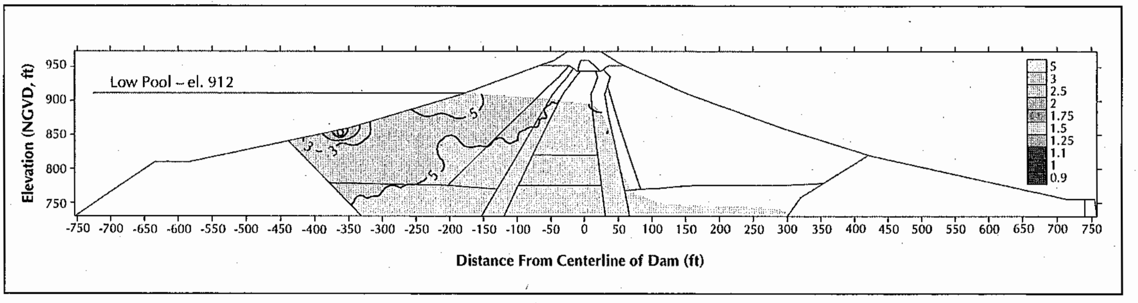

FIGURE 19. Factors of safety against liquefaction, Chicoutimi-Nord record, FLUSH analysis, peak base acceleration 0.12 g, low pool, two-dimensional analysis.

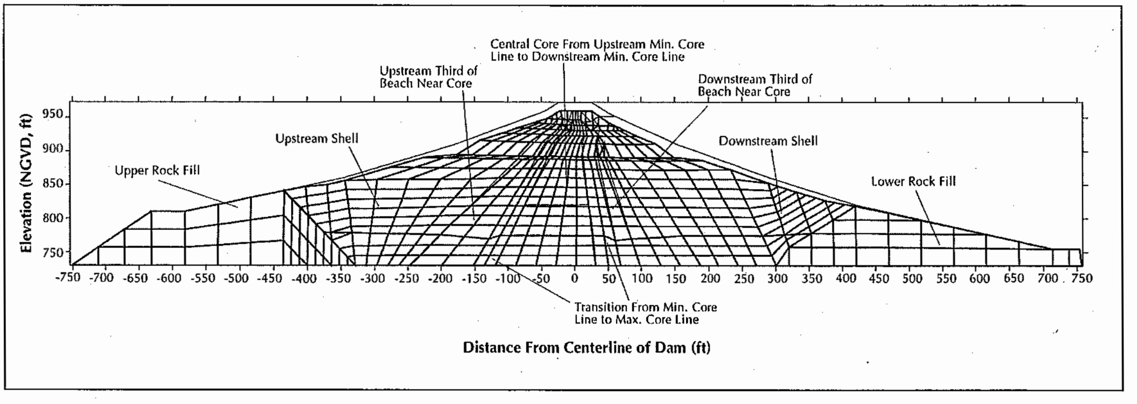

FIGURE 20. Deformed mesh (25-fold exaggeration), Cobble Mountain synthetic earthquake, QUAD-4M analysis, peak base acceleration 0.12 g, low pool, two-dimensional analysis.

Nord record. Both records were normalized to 0.12 g, and the analyses were done with QUAD-4M.

Figure 26 shows the settlement of the top surface corrected for three-dimensional effects. It corresponds to Figure 21 for the two-dimensional case. Figure 26 is for the Cobble Mountain synthetic record and QUAD-4M analysis. It also includes the results for 0.16 g input.

Peak Base Acceleration – 0.16 g. Figure 27 presents the contours of the factor of safety against liquefaction at full pool, including three-dimensional effects, for the QUAD-4M analysis with the Cobble Mountain synthetic record normalized to 0.16 g. The factors of safety for the Chicoutimi-Nord record at 0.16 g are contoured in Figure 28. The deformed mesh for full pool, with deformations exaggerated by a factor of 25, is plotted

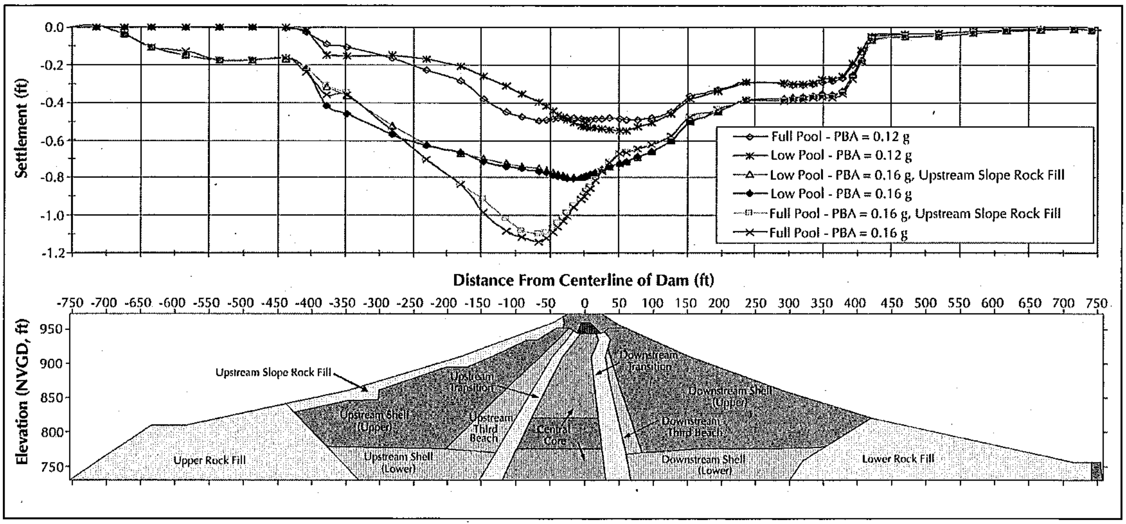

FIGURE 21. Estimated settlement along the top surface of the profile, two-dimensional QUAD-4M analysis, Cobble Mountain synthetic earthquake.

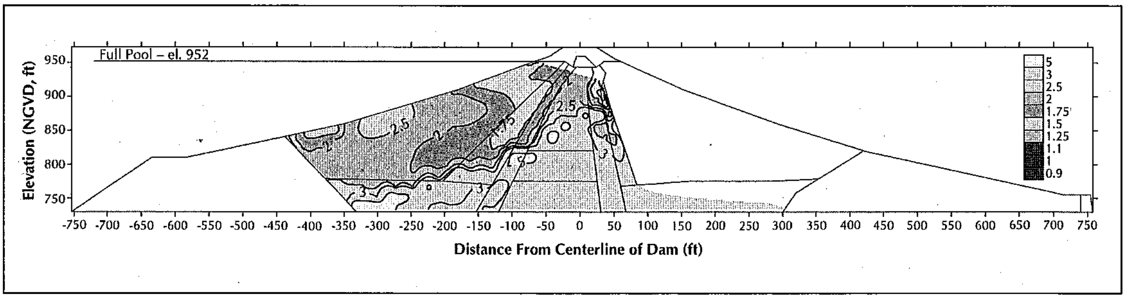

FIGURE 22. Factors of safety against liquefaction, Cobble Mountain synthetic earthquake, QUAD-4M analysis, peak base acceleration 0.12 g, full pool, pseudo-three-dimensional analysis.

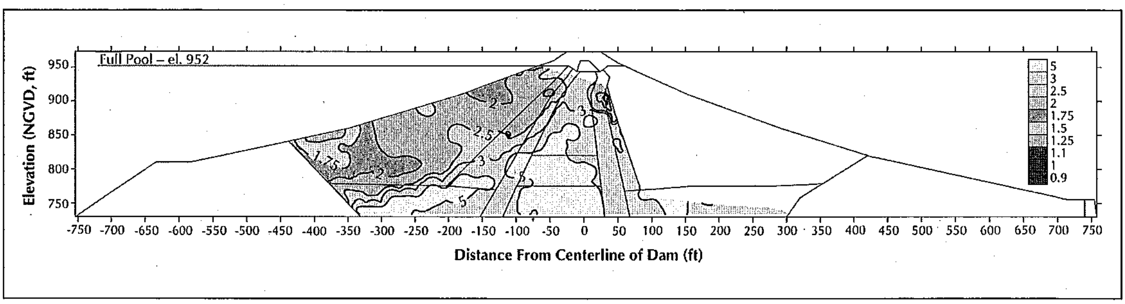

FIGURE 23. Factors of safety against liquefaction, Chicoutimi-Nord record, QUAD-4M analysis, peak base acceleration 0.12 g, full pool, pseudo-three-dimensional analysis.

in Figure 29 for the Cobble Mountain synthetic record.

The pseudo-three-dimensional analyses show that when the reservoir is at low pool, the factors of safety are similar and the deformations are less. However, in localized shallow zones beneath the upstream slope of the dam, where effective confining stresses are relatively low, initial computed factors of safety were as low as 0.9 to 1.0. These low values are artifacts of a conservative decision originally not to model the beneficial effects of the

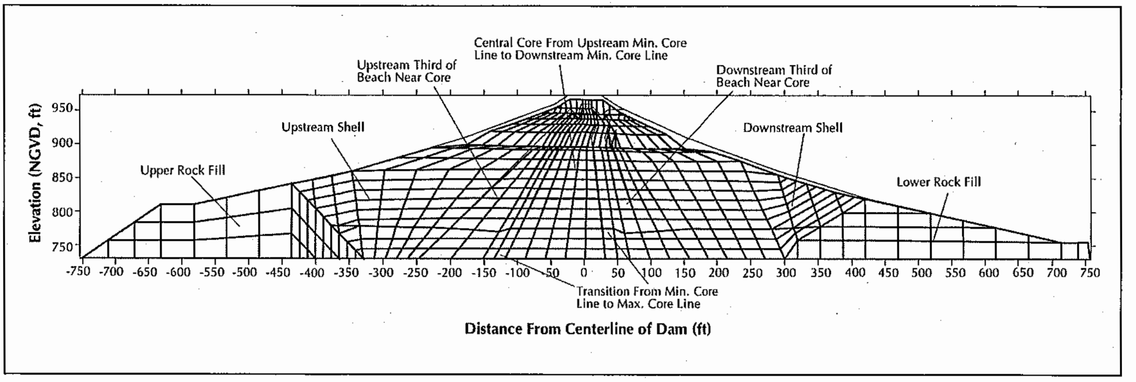

FIGURE 24. Deformed mesh (25-fold exaggeration), Cobble Mountain synthetic earthquake, QUAD-4M analysis, peak base acceleration 0.12 g, full pool, pseudo-three-dimensional analysis.

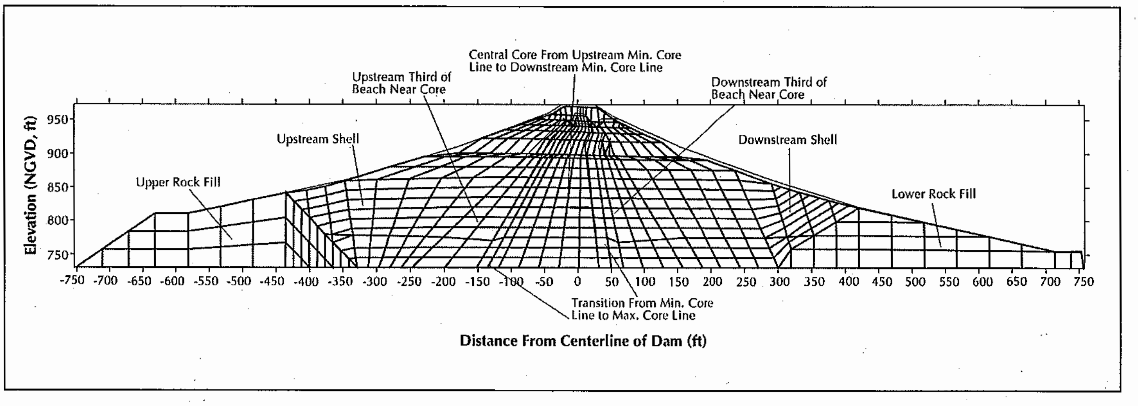

FIGURE 25. Deformed mesh (25-fold exaggeration), Chicoutimi-Nord record, QUAD-4M analysis, peak base acceleration 0.12 g, full pool, pseudo-three-dimensional analysis.

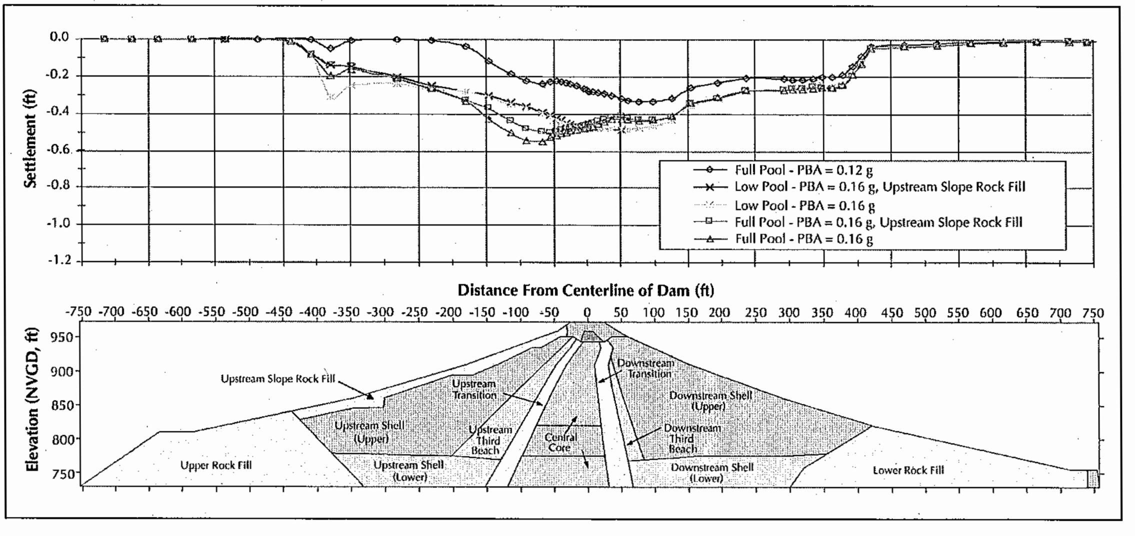

FIGURE 26. Estimated settlement along the top surface of profile, pseudo-three-dimensional QUAD-4M analysis, Cobble Mountain synthetic earthquake, full and low pool, 0.12 g and 0.16 g peak base accelerations.

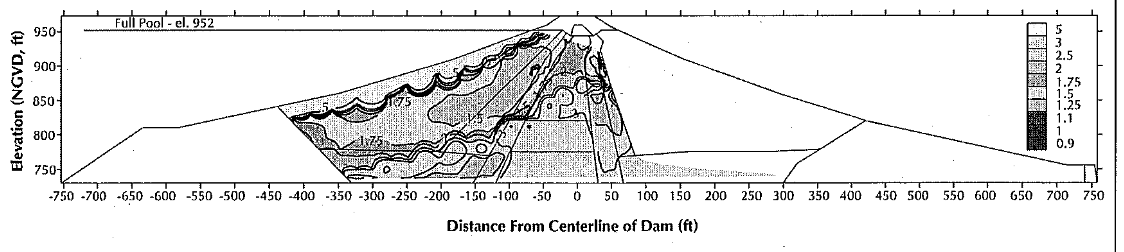

FIGURE 27. Factors of safety against liquefaction, Cobble Mountain synthetic earthquake, QUAD-4M analysis, peak base acceleration 0.16 g, full pool, upstream slope rockfill pseudo-three-dimensional analysis.

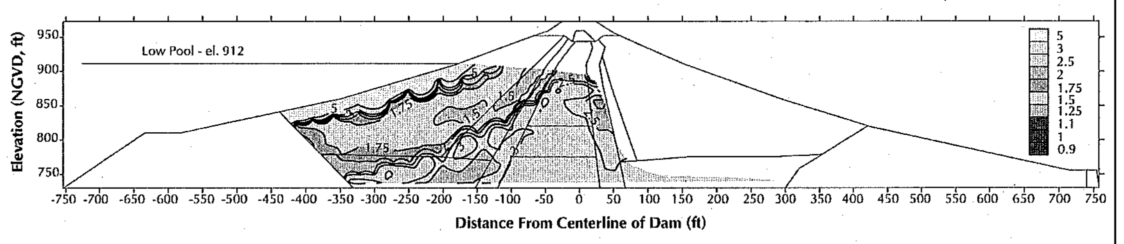

FIGURE 28. Factors of safety against liquefaction, Cobble Mountain synthetic earthquake, QUAD-4M analysis, peak base acceleration 0.16 g, low pool, upstream slope rockfill pseudo-three-dimensional analysis.

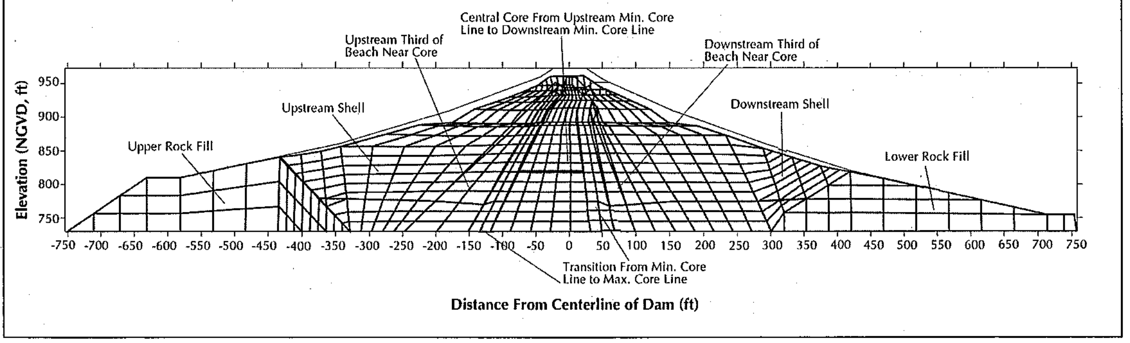

FIGURE 29. Deformed mesh (25-fold exaggeration), Cobble Mountain synthetic earthquake, QUAD-4M analysis, peak base acceleration 0.16 g, full pool, pseudo-three-dimensional analysis.

5- to 15-foot-thick layer of surficial crushed rock fill on the upstream slope. To evaluate these effects, this layer was modeled in two-dimensional QUAD-4M analyses for high and low pool levels using the Cobble Mountain synthetic record at 0.16 g. Computed factors of safety against liquefaction in the shallow areas along the upstream slope were at least 5.0. Figure 28 is one of the two design cases.

Figure 26 shows the settlement of the top surface corrected for three-dimensional effects. This figure is for the Cobble Mountain record and QUAD-4M analysis. It also includes the results for 0.12 g input.

Peak Base Acceleration – 0.204 g. The possible effects of an earthquake with a peak base acceleration of 0.204 g were investigated using the Chicoutimi-Nord earthquake record since

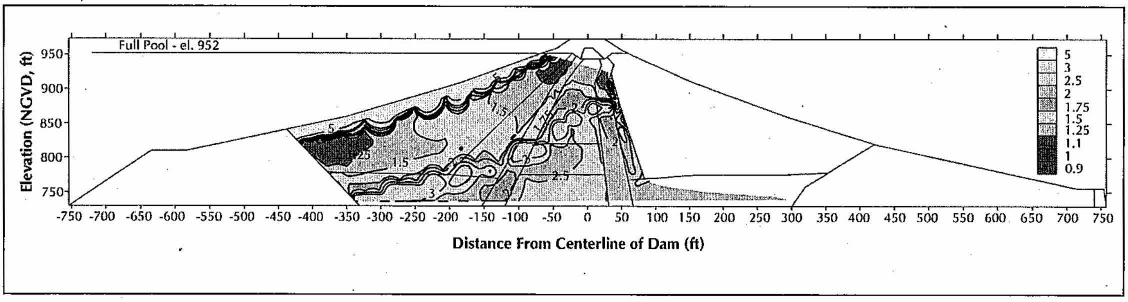

FIGURE 30. Factors of safety against liquefaction, Chicoutimi-Nord record, QUAD-4M analysis, peak base acceleration 0.204 g, full pool, upstream slope rockfill pseudo-three-dimensional analysis.

this record is judged to be more representative of the motions that could be expected from a synthetic earthquake record. Factors of safety against liquefaction, including three-dimensional effects and upstream slope rockfill, are plotted in Figures 30 and 31 for full pool and low pool, respectively. Figure 31 is the other of the two design cases. It contains a larger zone with the lowest range of factor of safety between 1.0 and 1.25 in comparison to the full pool case of Figure 30. When the upstream rockfill zone was not modeled initially the factor of safety for a significant size zone with the low pool cases was between 1.0 and 0.5. This result is entirely due to a modeling artifact. Figure 32 shows a typical deformed mesh for all cases, again with 25-fold exaggeration. Figure 33 shows the settlement of the top surface of the maximum section of the dam.

Conclusions

Liquefaction Potential. For the earthquake records and material properties considered in these analyses, there are adequate factors of safety against liquefaction throughout the central cross-section of the dam. The most severe case for the pseudo-three-dimensional analysis, which is judged to be the most appropriate for the geometry of this dam, occurs at low pool. Although three-dimensional considerations do affect the results (for example, somewhat reducing the factors of safety against liquefaction for the Chicoutimi-Nord record), the computed factors of safety remain adequate. When the upstream rockfill is included in the model, the pseudo-three-dimensional cases with full pool give factors of safety against liquefaction of 1.25 to 1.50 or larger for all cases within Material 4 (lower upstream and downstream shells) and Materials 1 and 9 (central core). From the exterior slopes of the dam inward towards the core, the computed factors of safety against liquefaction are at least 1.0 to 1.1, 1.1 to 1.25 and 1.25 to 1.5 within Material 5 (upper upstream shell), Material 3 (upstream and downstream one-third beach-

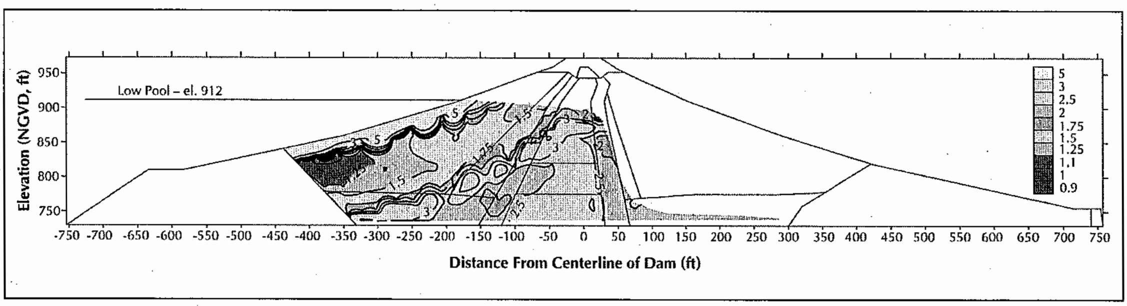

FIGURE 31. Factors of safety against liquefaction, Chicoutimi-Nord record, QUAD-4M analysis, peak base acceleration 0.204 g, low pool, upstream slope rockfill pseudo-three-dimensional analysis.

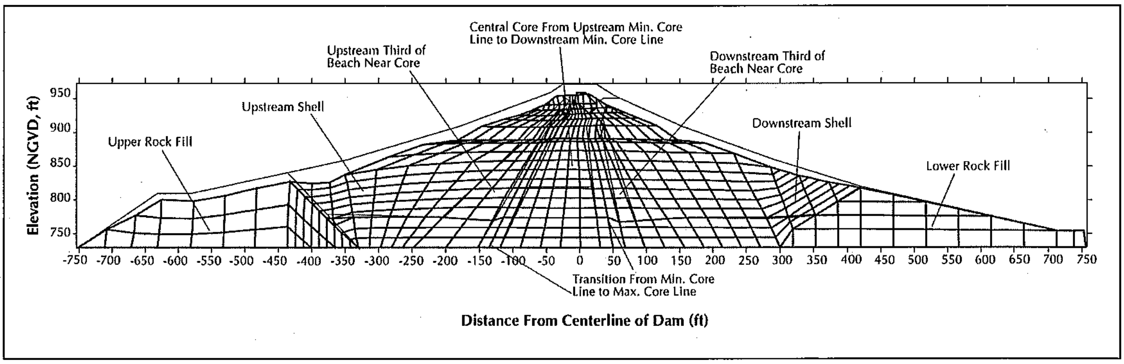

FIGURE 32. Deformed mesh (25-fold exaggeration), Chicoutimi-Nord record, QUAD-4M analysis, peak base acceleration 0.204 g, full pool, pseudo-three-dimensional analysis.

es) and Material 2 (upstream and downstream transitions), respectively. As would be expected, as the input acceleration increases, the factors of safety decrease.

Seismic Deformations. The estimated deformations of the dam under the seismic excitations are also acceptable. The most severe results are for an input peak acceleration of 0.204 g, which gives a maximum settlement of about 1.2 feet. In view of the many approximations in the analysis, it would be good practice to double this result, but the resulting settlement is still only approximately 2 feet. Also, it should be noted that the maximum settlement does not occur at the crest of the dam but at a point about halfway along the upstream slope surface. The computed crest settlement is in all cases less than 0.8 feet, which when doubled gives less than 1.6 feet, which correspond to small vertical strains on the order of 1 percent.

Impacts on Performance. The freeboard (vertical distance from dam crest to normal full reservoir pool) is 20 feet for this structure and it would not be compromised by deformations of the order of magnitude estimated from these analyses.

Analytical Procedures. These analyses employed six different finite element programs: SEEP/W, a proprietary flow program, SIGMA/W, QUAD-4M, FLUSH and PC-FEAP. The basic finite element mesh remained the same. Small, special-purpose programs

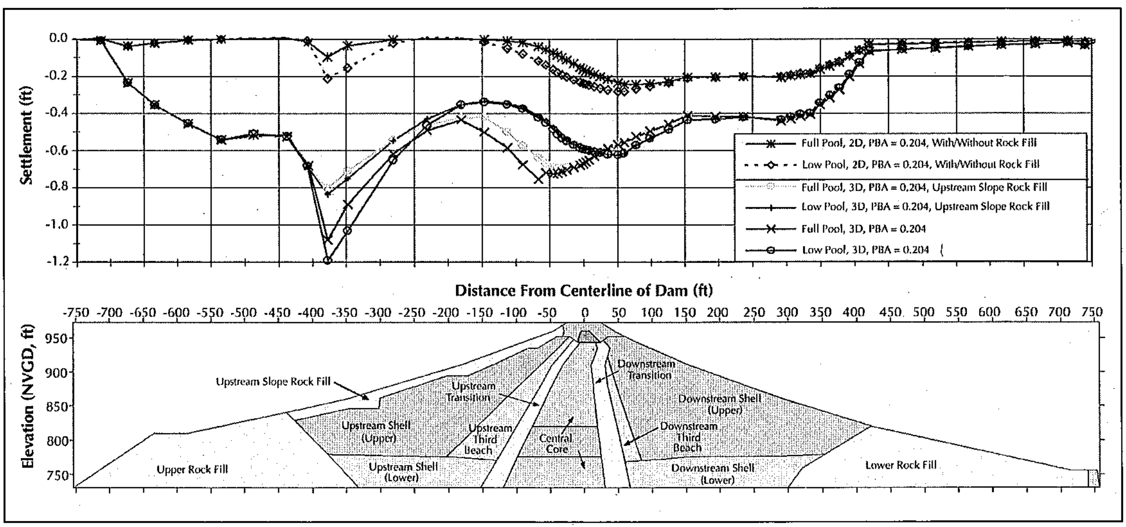

FIGURE 33. Estimated settlement along the top surface of profile, QUAD-4M analysis, Chicoutimi-Nord record, 0.204 g peak base acceleration.

were used to evaluate intermediate results, to compute local factors of safety or volume changes, and to pass data between the finite element programs. These programs worked element by element, preparing printed output, output suitable for plotting or output in appropriate format for input to subsequent finite element analyses. This approach had many advantages, including:

- using readily available, proven software;
- obtaining interim results, which could be studied to guide further analyses;
- eliminating the expense and delay of writing and debugging large new software; and,
- avoiding the rigidity of a large, canned program.

This approach does require that the analysts be able to access and to modify the input and output files for the various programs.

Presenting Results. The project engineers, the seismic response consultants and the client considered the analytical program a success. A major factor in this achievement was the presentation of results of the analyses in the form of color plots for a personal-computer-based presentation. In order to do so, the output from finite element programs was processed (without distortion) to accommodate the software needed to create the contour plots, plots of deformed meshes and plots of surface settlement. The results were well worth the effort.

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ALFREDO URZUA *is the President of Prototype Engineering, Inc., in Winchester, Massachusetts. He received his Civil Engineering degree from the University of Chile, and a masters' degree and a Ph.D. in Civil Engineering from the Massachusetts Institute of Technology. He has over 25 years of experience in earthquake engineering, soil dynamics and numerical methods.*

JOHN T. CHRISTIAN, *Ph.D., P.E., has over forty years' experience in geotechnical engineering, including work on earth dams, finite elements, soil dynamics and earthquake engineering. He is an Honorary Member of BSCES, and Honorary member of ASCE and a member of the National Academy of Engineering. He will deliver the 38th Terzaghi Lecture in June 2003.*

WILLIAM H. HOVER, *P.E., is a senior principal and director of GZA GeoEnvironmental Technologies, Inc. He served as Principal-in-Charge of GZA's efforts on this project, and has evaluated many of the largest embankment and gravity dams and associated water supply systems and infrastructure in New England and New York.*

IVAN A. HEE *received a B.E. degree in Civil Engineering from Stevens Institute of Technology and a M.S. degree in Civil Engineering from Virginia Tech. He is currently employed as a geotechnical engineer with GZA GeoEnvironmental, Inc.*

STANLEY M. BEMBEN, *P.E. is a Professor Emeritus of the University of Massachusetts, Amherst. He received his B.S.C.E. from UMass, his M.S.C.E. from the University of Illinois and his Ph.D. from Cornell University. He is a consultant in geotechnical and forensic engineering and served as the lead project engineer for SWSC.*

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Effective Facilities Planning Ensured a Successful Boston Harbor Cleanup

Any megaproject requires an extensive and thorough assessment of the design and construction requirements and their technical, regulatory, financial and communal effects.

RICHARD D. FOX, WILLIAM F. CALLAHAN & WALTER G. ARMSTRONG

Everyone agrees that effective planning pays off. Yet, while the concept is philosophically irrefutable, it can be difficult to implement, particularly in the face of a crisis and the pressing need to act. The tendency to move forward without proper planning is a well-known human trait — and one that contradicts our logical understanding of the need to invest in planning for the long term. However, investing the appropriate resources to study and plan before taking action is essential to ensure a successful outcome, and the facilities plan developed for the Boston Harbor Project (BHP) is a fine example of this truism.

Completed in 1988 and further refined seven years later, the BHP's Secondary Treatment Facilities Plan proved a reliable, innovative and forward-thinking guide for what was one of the most complex wastewater treatment projects ever undertaken in the United States. This plan:

- detailed an extremely effective management structure,
- established the technical components for secondary treatment of wastewater,
- required minimal changes (thereby keeping the massive design and construction project on schedule),
- outlined measures to manage costs and other institutional factors, and
- provided for a wide range of public support.

The plan's scope — which encompassed an unusually broad range of technical, regulato-

FIGURE 1. Deer Island in 2002.

ry, financial, public and community-related concerns — ensured that the project would "secure and sustain the acceptance and support of the diverse community, government, and business interests that it affects."[1] The process of developing the plan then was not merely a technical exercise resulting in a technical document, but an intense and dynamic program that produced a document that would prove a valuable guide through the thirteen-year design, construction and startup process, and is expected to remain viable through 2020.

The harbor's cleanup has been widely hailed as a model of effective consensus building, design and construction management on a "mega" scale, and as a model of technical innovation as well. The overall planning approach and individual plan components contributed to an extremely successful project outcome. The project was completed in November 2001, with the performance of final site work landscaping and paving (see Figure 1). The final treatment facilities — the 9.5-mile-long effluent outfall tunnel and the third battery of the secondary treatment facility —went into operation on September 6, 2000, and March 8, 2001, respectively. Of the fifteen schedule milestones established in the federal court order that launched the BHP, all of them have been completed. Moreover, the project finished about 15 percent (or $500 million) under the original budget. Additionally, the change order percentage on plant construction averaged 10.8 percent of the award value, only slightly above the 10 percent target established for the project. Likewise, the costs of managing the program represented 10 percent of total program costs. Most importantly, the finished facilities are treating and disposing of the wastewater generated by 2.5 million Boston-area residents and 5,500 businesses — meeting the permit requirements and resulting in demonstrable water quality improvements.

Setting the Stage for Facilities Planning

The disposal of sewage and other waste into

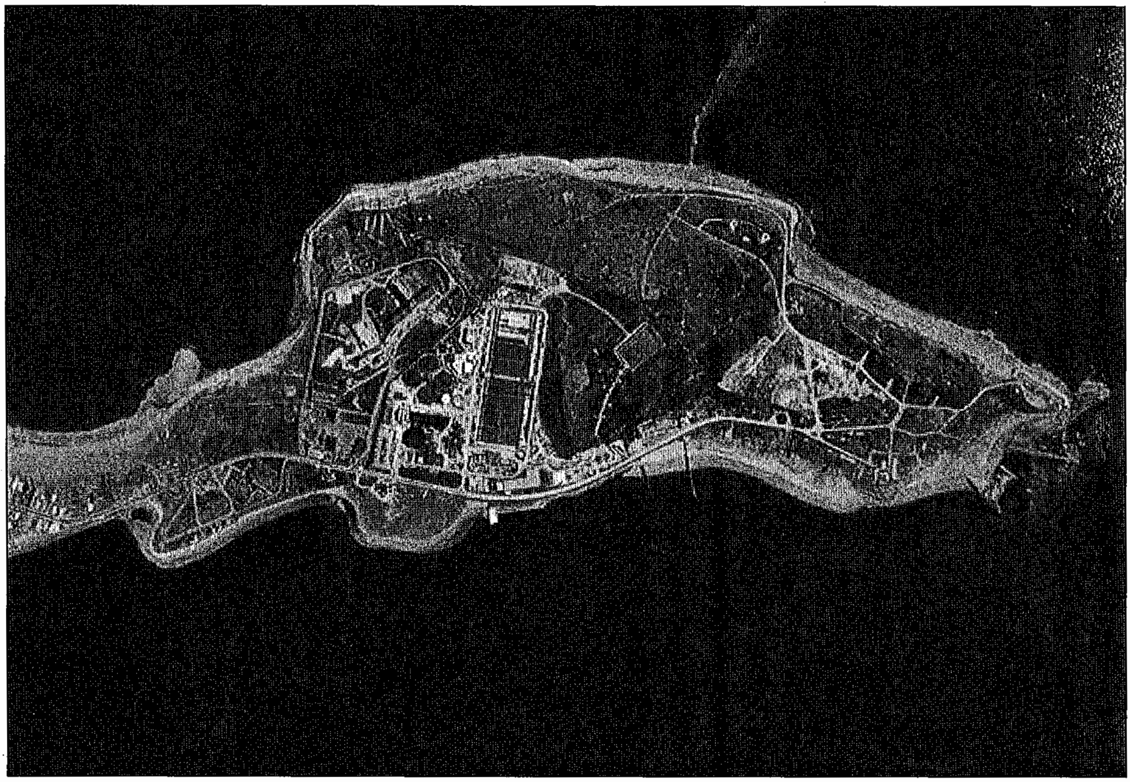

FIGURE 2. Deer Island before the construction of the new facilities.

historic Boston Harbor for 300 years had markedly reduced water quality, deteriorated habitat, polluted beaches and affected the quality of life for residents in neighboring areas. The two primary treatment plants at Nut Island and Deer Island had deteriorated and were inadequate to handle the volume and characteristics of the wastewater transported to them for treatment (see Figure 2). Regulators and neighboring towns alike recognized that the combined discharge of both primary effluent and sludge from these facilities to the harbor's relatively shallow waters posed a severe strain on its ecosystem.

The 1982 litigation by the City of Quincy, site of the then 30-year old Nut Island primary treatment plant, ultimately led to the creation of the Massachusetts Water Resources Authority (MWRA) in 1984 to operate, regulate, finance, rehabilitate and modernize the waterworks and sewerage systems serving greater Boston. Today, the MWRA provides a combination of water supply and distribution services, as well as wastewater collection and treatment services, to cities, towns and special purpose districts within the Commonwealth of Massachusetts.

Nearly as quickly as it was created, the MWRA found itself in court to begin the long process of planning for, and ultimately executing, a comprehensive program to clean up Boston Harbor. In 1986, the MWRA formally entered into a federal court order that outlined fifteen critical schedule milestones related to the construction of new wastewater facilities to begin in October 1990 and culminate in December 1999 with all treatment facilities constructed. Failure to meet this schedule could have resulted in sanctions as severe as $10,000 in fines daily for each violation of the Clean Water Act. The MWRA recognized the need to develop a comprehensive plan that would guide the process. Adding to the many challenges already inherent to the process was the fact that the MWRA was a new organization — one that had not yet had opportunities to establish itself as a credible or valuable water authority in the eyes of the public and others. In fact, the plaintiffs in this suit did not believe that the MWRA had the expertise necessary to oversee such a large project. But as time went on, the plaintiffs came to respect the MWRA and to support its comprehensive efforts to improve water quality in Boston Harbor.

Establishing the Course for the Cleanup

In 1986, the MWRA contracted with an engineering consultant to undertake the development of a facilities plan. As completed in 1988, the plan formed the foundation for the MWRA program to construct and operate new wastewater treatment facilities. Development of the facilities plan involved hundreds of meetings and difficult decisions about siting large and complex facilities, environmental protection and mitigation, as well as the logistics of construction in a densely populated urban environment. In fact, facility siting issues were so complex that they were addressed in a separate siting decision plan.

The MWRA used eight criteria to evaluate the eight site options presented in the draft environmental impact report (EIR). Of these, the MWRA determined that three criteria — implementability, impacts on neighbors and reliability — were neutral in the siting decision. The fourth criterion — the equitable distribution of regional impacts — favored options that located treatment facilities on Nut Island or Long Island. The other four criteria of harbor enhancement — impacts on cultural and natural resources, cost and non-environmental mitigation — favored Deer Island as the best site for the wastewater treatment facilities. After evaluating the criteria, the MWRA designated Deer Island as the most suitable site for the new wastewater treatment facilities. In addition, the final EIR included the MWRA's commitment to both short- and long-term mitigation measures to reduce impacts on communities where the facilities were to be constructed (including limits on noise and odors) and to the barging and busing of construction materials and workers to minimize negative impacts on local traffic patterns. The facilities plan recommended the facilities needed (including secondary treatment of a peak flow of 1,080 million gallons per day [mgd] in four batteries of pure-oxygen activated sludge and primary treatment for a peak flow of 1,270 mgd), provided preliminary design sketches and costs, and evaluated the environmental impacts and necessary mitigation measures. In the absence of extensive historical flow and load data, the plan provided for conservative capacities. It was understood that these capacities might be modified as the MWRA collected additional data a few years into the project. Notably, the plan also outlined significant commitments (made as part of the siting decision plan) to restrict noise and air emissions during both construction and facility operations and proposed bus, water and barge transportation to the site during construction so as not to burden nearby communities. Moreover, the plan provided for extensive community involvement, which was to prove critical as the project moved forward.

From the outset, the MWRA was committed to making the plan a model of public participation and consensus building, with the understanding that the plan must be supported by a diverse community that represented both private- and public-sector interests. Thus, as the planners noted, "the planning process was based not on technical strength alone, but also on the continual reconciliation of political, legal, environmental, economic, and community interests."[1]

As part of this planning process, major decisions were made to select an appropriate wastewater treatment process, to size and locate conduits and pumping stations, and to plan the initial site preparation program for construction of the Deer Island treatment facility. The team considered the following broad criteria in evaluating alternatives:

- Environmental criteria (including air emissions, noise, traffic and marine resources) as well as measurements of potential environmental impacts of each alternative.
- Technical criteria, which focused on engineering issues such as reliability, flexibility, constructibility, operational complexity, area requirements, staging requirements and power needs.

- Cost criteria, which presented the financial investment necessary to construct and operate the alternatives.
- Institutional criteria, which assessed the differences among alternatives according to the time required for construction and coordination among many public and private entities.

The resulting plan incorporated these four criteria and other considerations into recommendations presented in eight volumes, with more than 20 detailed technical appendices, as follows:

- Volume I — Executive Summary
- Volume II — Facilities Planning Background
- Volume III — Treatment Plant
- Volume IV — Inter-Island Conveyance System
- Volume V — Effluent Outfall
- Volume VI — Early Site Preparation
- Volume VII — Institutional Considerations
- Volume VIII — Public Participation and Responsiveness Summary

Four volumes alone (III through VI) addressed planning efforts for the new facilities needed to provide secondary treatment.

The facilities plan was completed early in 1988, and construction work officially began on the BHP that same year. During the next six years, the MWRA worked to substantially increase its database on influent flows and loads in preparation for the detailed design and construction of the appropriate secondary treatment facilities. Additionally, a 2-mgd pilot plant on Deer Island was constructed to obtain operating information specific to the plant wastewater. Simultaneously, increased attention nationwide on innovative and emerging technologies further encouraged the MWRA to reassess secondary treatment and sludge processing technologies at Deer Island.

In fact, the 1988 facilities plan and schedule had anticipated the need to collect exactly these kinds of additional data to refine the design of the secondary treatment facilities. Lack of reliable flow data led facilities planners to size the plant for the maximum transmission capacity to the Deer Island plant. Therefore, the facilities plan established sufficient flexibility in the design and construction schedule to provide an opportunity to reassess the capacity of the remaining half of the proposed secondary treatment facilities and associated residuals handling facilities. Beginning in 1993, after all the facilities proposed for primary treatment and the initial portions of the secondary treatment system were either under construction or had at least been designed, the planning team:

- Critically examined recent flow and load data.
- Generated performance goals and design criteria necessary to comply with anticipated water quality and National Pollutant Discharge Elimination System (NPDES) requirements.
- Reviewed recent innovative/emerging technologies (including chemically enhanced primary treatment) for possible application to the project.
- Validated design criteria through testing at the 2-mgd pilot plant.
- Evaluated alternative scenarios for completing the Deer Island facility in terms of its ability to meet standards, projected impacts on residuals processing, cost, operational flexibility, continuity with existing facilities and overall desirability.

The goal of this enhancement to the facilities plan was to recommend cost-effective facilities that would be able to meet NPDES secondary treatment requirements even during storm flows (when the MWRA's combined sewer overflow abatement program — concurrently being developed — would maximize flows to Deer Island). During the initial facilities plan, it was determined that during storm events not all flows would require secondary treatment and primary effluent could be blended with secondary effluent. These blended flows would comply with secondary treatment effluent requirements. Based on the new flow data, the team reassessed the capacity needed for the secondary treatment facilities. The testing program evaluated the effects of various blend ratios of conventional or chemically enhanced primary treatment with secondary treatment to determine the optimum-sized plant that would meet secondary effluent requirements during wet weather. Effluent variability data from similar plants and from the pilot plant helped construct frequency distributions for use in detailed mathematical modeling of the blended effluent's quality.

The modeling helped to validate a significant downsizing of secondary facilities required to meet all secondary standards during wet weather. The required capacity of the secondary facilities was determined to be 780 mgd, versus the 1,080-mgd capacity anticipated in the 1988 plan. This change in capacity meant, among other outcomes, that one of the four originally proposed batteries for secondary treatment and 25 percent of the residuals digesters would not be required, saving $160 million in capital costs.

Regulatory approval was achieved in 1995 when the U.S. Department of Environmental Protection and the federal court accepted the "Plan for Completion of Deer Island Facilities" based on the reassessment efforts.

Ensuring Long-Term Success Through Key Planning Elements

There is no question that even though the facilities plan was broad in its scope that it was also extremely thorough. It addressed all the necessary technical aspects for a complex program — requiring five volumes to do so — but also covered management issues, public involvement and education, and a host of institutional factors designed to facilitate the program and control costs.

A Unique Management Approach. Faced with a pressing court-ordered schedule, intense public demand for cost control and large logistical challenges, the MWRA needed to conceive an effective management structure that would smoothly move the project from the planning stage through design, construction and start-up. The MWRA needed to maintain adequate control over the design and construction of the new facilities, effectively manage the $4.0-billion project while simultaneously implementing a $100-million per year system-wide capital rehabilitation program and define and organize the roles of the private-sector resources.

In September 1987, the board of directors of the MWRA endorsed the concept of a unique three-way management scenario under which overall project control remained with the MWRA, but private consultants managed day-to-day construction activities and served as the lead design engineer. In this way, the owner provided strong overall direction through its own staff (the MWRA Program Management Division, which was dedicated solely to the BHP) and was supported by the expertise and resources of a private-sector construction management team. This management structure was first recommended in 1987 and formalized with the 1988 facilities plan. In 2000, as the project reached completion, the structure was reorganized, with the MWRA creating a Consolidated Operating Division, and the Program Management Division becoming a department within the larger operating entity. During the critical years of the BHP, the dedicated Program Management Division structure provided several benefits:

- Created a team with the sole responsibility and total focus to get the job done.
- Having a team dedicated to the project prevented it from consuming the resources of other MWRA divisions, which had their own ongoing responsibilities for large capital improvement projects.
- Gave the MWRA the opportunity to identify and recruit qualified people both from within and outside its organization.
- Provided close coordination between construction and support activities, such as logistics, safety, labor relations and owner-supplied services.

Earning Public Support. The facilities plan notes that, "[t]hrough the [comprehensive public participation effort], the [MWRA]'s dialogue with the public has been ongoing, and important policy decisions have been made and will continue to be made within the context of maximum public knowledge and participation."[1] More than 300 public meetings were held, many of them resulting in

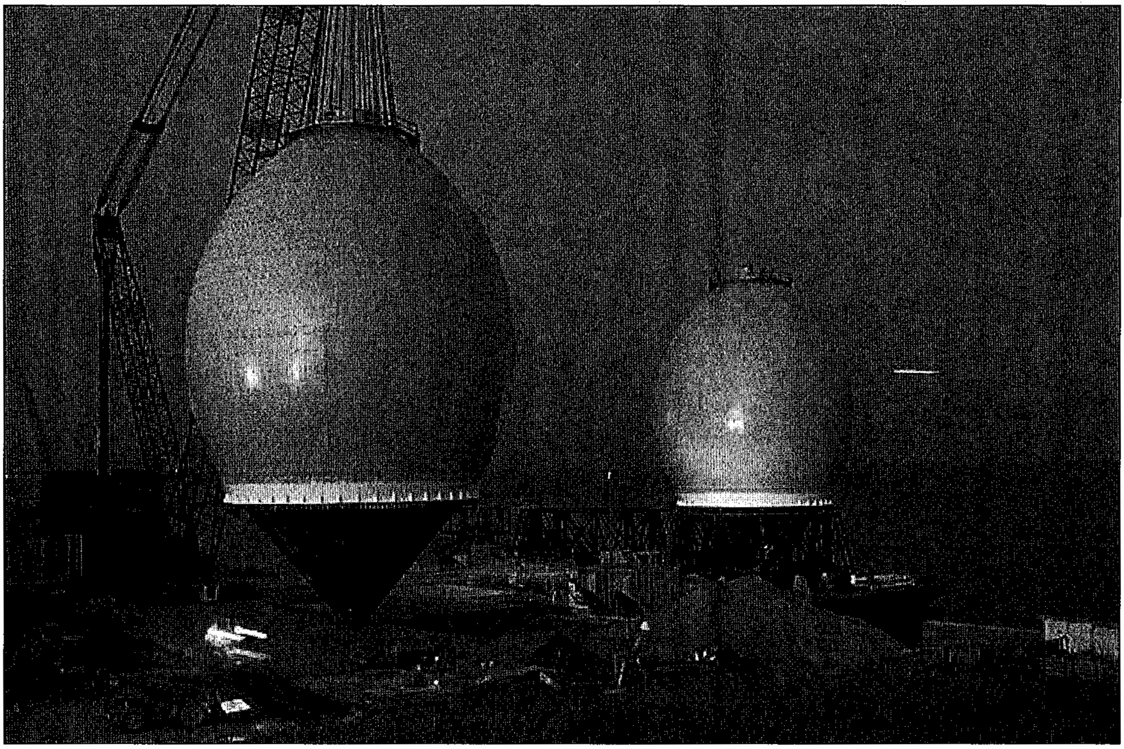

FIGURE 3. An egg digester being lifted into place.

agreements and formal memoranda of understanding that addressed the concerns of various community groups and towns. Three negotiated terms were especially key: the need to ferry people and equipment rather than drive vehicles, as well as defined noise and odor limits. The agreement to use barges or ferries reduced the need for truck and other construction vehicle traffic through Boston and the abutting town of Winthrop. The creation of a landscaped hill at Deer Island's northern tip minimized construction-related noise impacts on Winthrop, minimized the amount of excavate removed from the island and provided a permanent visual barrier for the town that screens the plant from view. Odor control measures were also incorporated into the facilities' designs.

Similarly, an unusually aggressive schedule for completing the primary facilities was intentionally established, partly so that the public and the regulators would witness tangible progress toward remediating the harbor as early as possible. In addition, the plan provided a way for the public to begin seeing significant improvements in the water quality of Boston Harbor through two early court milestones, the cessation of scum and sludge discharges into the harbor by the end of 1989 and 1991, respectively. As a result, visible improvements were apparent at a time when water and sewer rates were rising.

Achieving Technical Accuracy. From 1988 until the project completion, the basic layout of the planned facilities changed minimally, testament to the exhaustiveness of the plan preparation and the collective abilities of the BHP team to design and construct the facilities as planned. The integrity of the designs conceptualized in the facilities plan led to expeditious detailed design and corresponding adherence to the schedule. The application of innovative approaches, such as the use of stacked clarifiers to minimize the facilities' footprint, was facilitated by the plan. Egg-shaped digesters – a technology that had been used in Western Europe – were selected because of their more efficient mixing abilities and reduced maintenance requirements (see Figure 3). Like the stacked clarifiers, the eggs provided a smaller footprint that was easier to accommodate in the limited space available on Deer Island. Today, the unit capacity of the egg digesters is among the largest presently operating, and the concentration of twelve units on one site make the Deer Island installation one of the largest in the world. Other technical innovations, such as a large onsite power plant and hydro-electric turbine facility, also addressed cost sensitivities.

Combining Facilities Planning With Scheduling. The contracted engineering consultant's involvement in schedule development actually preceded development of the facilities plan, when the consultant helped the MWRA develop and negotiate a schedule for the court order – essentially the same schedule that was later incorporated into the facilities plan. In addition to the project's valuable public support benefits, the incorporation of the schedule into the facilities plan helped to control costs. The early schedule development, along with permit packaging techniques, also allowed the MWRA and its program manager to monitor and expedite the regulatory review process during design and construction. Careful scheduling also made it possible to coordinate the concurrent Massachusetts Environmental Policy Act EIR process and the U.S. Environmental Protection Agency environmental impact statement (EIS).

Monitoring Water Quality. The MWRA knew that it would need to justify the large expenditures of public funds being used for the project, so in 1987 it formed a Harbor Studies Group specifically charged with the task of tracking water quality improvements directly resulting from the project and developing the baseline data to determine effects on receiving waters over time from the outfall tunnel. The data from the monitoring program allowed the MWRA to identify sources of contaminants and prioritize spending. Finally, the monitoring program gave the harbor project added scientific credibility and gave the public the needed assurance that the MWRA would not allow the harbor to return to its previous polluted condition.

Managing Costs. The $3.5-billion price tag associated with this mammoth project subjected MWRA customers to a substantial financial burden, with water and sewer rates quadrupling over the life of the project. Further complicating the situation was the fact that the Massachusetts economy, which boomed throughout much of the 1980s, began to stall just as construction was about to begin on the project's first phases. Building on the cost control approaches set forth in the facilities plan, the MWRA adopted a number of strategies to control costs:

- A design management structure that focused on controlling costs through the oversight provided by the lead design engineer, the innovative use of computer-assisted design and the early incorporation of cost, constructibility and operability concerns into the design.
- The logical packaging of construction contracts to create maximum price competition, facilitate contract management and maximize economy of scale. The facilities plan organized the program into approximately ten packages, later refined into more than 160 separate design and construction contracts. The MWRA and its ratepayers gained several advantages from this type of contracting approach. These benefits helped maintain the schedule and helped organize the project into discrete, operable units, thereby making the project more manageable and avoiding the undesirable situation of having to delay one contract while waiting for another to go online. These contracts were then assembled into biddable and bondable packages that facilitated bidding by local firms – important to the local economy and to the MWRA's commitment to the community.
- The use of an aggressive outreach effort to attract bidders, which resulted in work being awarded to local firms approximately 70 percent of the time. These bids were generally below engineers' estimates.
- Detailed staffing projections and procedures for identifying staffing needs and for recruiting and training qualified staff to participate in the project.

- The use of long-term contracts to stabilize the costs of key construction support services, such as the water transportation system and the onsite supply of power, concrete and fuel.
- A carefully conceived program covering the logistics and complexities of executing large construction contracts on a peninsula – and one that, through agreement with the nearest town, could only be reached almost entirely by water. The team was only permitted to move eight construction vehicles per day over the road network. The site lacked sufficient power to operate the equipment needed to build the treatment facilities. Nor did it provide any of the conveniences of the typical construction site, such as the ability to truck in concrete, provide food for workers or dispose of trash. Instead, all these considerations had to be addressed through the facilities plan, which provided a program to make Deer Island self-sufficient for construction. The plan conceptualized this network of support services and facilities and it set forth recommendations and procedures for construction utilities, an onsite concrete plant, a backup power plant, a dedicated hazardous waste management facility, a first aid station, a fuel station, a construction debris pickup center, employee transportation, street sweeping and the many other logistical considerations needed to support construction.

The uninflated total cost of the program was estimated in the facilities plan to be $2.7 billion in 1988 dollars. Using mid-1980s inflation rates for Boston area construction, the inflated estimated price tag was expected to be $6.1 billion. Over the past decade, the program grew at a rate of 2.3 percent per year through scope changes, inflation and other factors. However, the final cost is still estimated at $3.5 billion, owing to many factors, but in part to the efficacy of the facilities plan.

Summary

The facilities planning process for the BHP was based on the continued reconciliation of political, legal, environmental, economic and community interests, in addition to technical strength. For thirteen years, it served as effective guidance for one of the world's most challenging public works projects, and offers a solid model for other complex projects.

ACKNOWLEDGMENTS – *CDM was contracted by the MWRA in 1986 to develop the facilities plan for the Boston Harbor Project. The authors wish to acknowledge the helpful input of several individuals, including Ralph Wallace and Dave Reilly of the MWRA, Dr. Michael Connor from the New England Aquarium, and John Gall and Robert Otoski of CDM.*

RICHARD D. FOX *is president of CDM (Cambridge, Mass.). Under CDM's contract with the MWRA in the early 1980s, he served as the court's expert in the earliest discussions of scheduling for the BHP, and was integral in establishing the complete sequence of project activities. He went on to play a central role in the development of the secondary treatment facilities plan, and joined MWRA in 1988 to serve as director of the Program Management Division. In 1992, he rejoined CDM.*

WILLIAM F. CALLAHAN *is a senior vice president with CDM. His involvement in the Boston Harbor Project extends to 1984. He served as CDM's project manager on the secondary treatment facilities plan development from 1986 through 1988 and again in 1993–94.*

WALTER G. ARMSTRONG *is a senior vice president with CDM. Beginning in 1987, he was an integral member of the CDM team working on the secondary treatment facilities plan. In 1988, he joined MWRA as deputy director of the Program Management Division. In 1992, he assumed the role of Program Management Division director, a position he held until returning to CDM in 1999.*

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Pioneers in Soil Mechanics: The Harvard/MIT Heritage

Five preeminent engineers give their first-hand accounts about how the discipline of geotechnical engineering developed in the Boston area during the twentieth century.

ANNI H. AUTIO & MICHAEL A. MCCAFFREY

To commemorate the beginnings and accomplishments of Boston's pioneers in soil mechanics, the Boston Society of Civil Engineers Section/ASCE (BSCES) sponsored a history-in-the-making panel discussion called the "Pioneers in Soil Mechanics: The Harvard/MIT Heritage" at the 1998 ASCE Convention in Boston on October 20, 1998. Over 150 civil engineering professionals from around the world attended this very well received presentation. The presentation's focus was on the contributions by Boston's pioneers in soil mechanics at Harvard University and the Massachusetts Institute of Technology (MIT) who shaped and advanced the geotechnical engineering profession.

The distinguished panelists were Dr. Harl P. Aldrich, Jr., Dr. Ralph B. Peck, Dr. Robert V. Whitman and Dr. Steve J. Poulos. Dr. Ronald C. Hirschfeld, 1998 ASCE Honorary Member, moderated the panel discussion. The panelists shared their personal remarks with the audience, which stimulated an open discussion that followed.

Remarks by each presenter are published here to record this commemorative event that occurred during the 150th anniversary of BSCES and near the 75th anniversary of modern soil mechanics and geotechnical engineering. The intent is to promote follow-up discussions so that the unwritten history preserved in personal memories can be documented for the benefit of future generations of civil engineers who will advance the accomplishments made thus far.

Opening Remarks

By RONALD C. HIRSCHFELD, Moderator, Founding Principal (retired), GEI Consultants, Inc., Winchester, Massachusetts

Modern soil mechanics is usually dated from Karl Terzaghi's pioneering research from 1916 to 1925 at Robert College in Istanbul and the publication of his book *Erdbaumechanik* in 1925.

A circular slice of a historic wooden pile with an engraved plate was presented by BSCES to these five speakers to commemorate the era when this field was being rapidly developed in Boston by the pioneers in soil mechanics. The pile was removed in 1998 to allow construction of the new Central Artery Tunnel. This pile plaque is a fitting memento for these students of the pioneers in soil mechanics. From left to right, Harl P. Aldrich, Jr., Robert V. Whitman, Ronald C. Hirschfeld, Ralph B. Peck and Steve J. Poulos.

Initially, Terzaghi worked briefly in the United States from 1912 to 1913, but when he returned to the United States in 1925 he sowed the seeds for a remarkable introduction and flowering of soil mechanics at Harvard and MIT and fostered its spread throughout the United States.

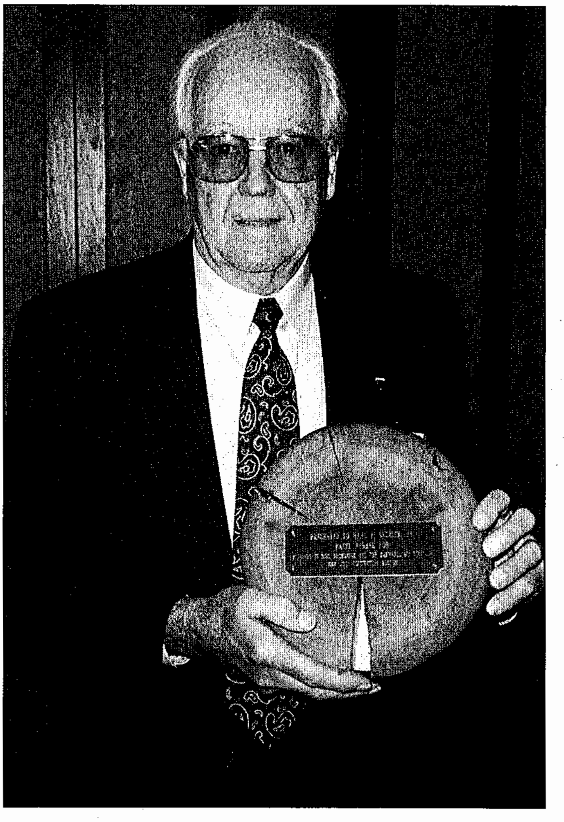
Our four panelists will give a brief history of what happened at Harvard and MIT from 1925 to 1998. Each of the panelists has been associated with Harvard, MIT or both.

Harl P. Aldrich, Jr., received his doctorate in soil mechanics at MIT, and after several years on the MIT faculty, he and Jim Haley founded the firm Haley & Aldrich. Harl Aldrich is the dean of civil engineers in the Boston area (and was recognized in December 1999 when the Conference Center at The Engineering Center in Boston was named after him and his wife, Lois). Aldrich will cover the arrival of Terzaghi at MIT in 1925 and the subsequent developments at MIT up to 1950.

Ralph B. Peck earned his doctorate in structural engineering at Rensselaer Polytechnic Institute and came to Harvard to study soil mechanics. Professor Terzaghi recognized Peck's talents and soon sent him to Chicago to be his representative on the construction of the Chicago subway. Terzaghi and Peck co-authored the bible of soil mechanics, *Soil Mechanics in Engineering Practice,* and Peck went on to the University of Illinois where he established an outstanding program in soil mechanics. He is the outstanding geotechnical engineer in the world today. Peck will discuss Terzaghi's career at Harvard and the First International Conference on Soil Mechanics and Foundation Engineering.

Robert V. Whitman received his doctorate at MIT and spent his entire career on the faculty at MIT. Both of us served in the Civil Engineer Corps of the U.S. Navy and were classmates at the Officer Candidate School (OCS) in Newport, Rhode Island. Whitman graduated with the highest academic average

Ronald C. Hirschfeld.



Harl P. Aldrich, Jr.

of anyone who had gone to the Navy OCS up to that time. He will discuss the evolution of soil mechanics at MIT from 1950 to 1998.

Steve J. Poulos is the only one of our panelists who holds degrees from both Harvard and from MIT, a bachelor's degree and a master's degree (the latter in Geotechnical and Hydraulics) from MIT and a doctorate in soil mechanics from Harvard. Poulos taught at Harvard for six years and then co-founded Geotechnical Engineers, Inc., with Dan LaGatta, Dick Murdock and myself. We edited the *Casagrande Volume, Embankment-Dam Engineering*. Poulos will discuss Casagrande's career at Harvard.

Following all of the panel presentations, brief remarks will be entertained from members of the audience. From the looks of it, many have studied at Harvard and MIT and have spread the gospel of soil mechanics throughout the United States and around the world.

As to be expected, there has been a friendly rivalry between Harvard and MIT for many years. It is often said that, "Harvard humanizes the scientist and MIT simonizes the humanist."

The Early Years at MIT, 1925-1950

By HARL P. ALDRICH, JR., Chairman Emeritus (retired), Haley & Aldrich, Inc., Boston, Massachusetts

MIT and Harvard, through research, education and publications, played preeminent roles in establishing soil mechanics (now geotechnical engineering) as an important discipline of civil engineering. If we acknowledge that Dr. Karl Terzaghi was the founder of soil mechanics as we know it today, then it follows that his arrival at MIT in 1925 marked its introduction to the United States. Within ten years, by the time of the First International Conference on Soil Mechanics and Foundation Engineering held at Harvard in 1936, major laboratories and courses in soil mechanics had been established at universities throughout the United States and abroad.

In 1925, at the age of 42 and after seven years of patient experimentation at Robert College in Istanbul, Turkey, where he was Professor of Civil Engineering, the Czech-born Terzaghi published a lengthy book in German entitled *Erdbaumechanik (Soil Mechanics)*.

Professor Charles M. Spofford, Head of the Civil and Sanitary Engineering Department at MIT, had heard of Terzaghi's work and learned that Terzaghi would take a year's leave of absence from Robert College. In May 1925, he wrote to Terzaghi and offered him a position at MIT as Lecturer on Foundations and Soil Mechanics and Research Associate. Terzaghi accepted since his career was reaching a turning point and he felt that if he were to remain solely in Turkey his reputation would become limited.

John R. Freeman, an alumnus of MIT, Class of 1876, met Terzaghi in late 1925 and became an early advocate. He worked hard to expose the engineering community to Terzaghi's ideas. Freeman used his influence as past president of ASCE to arrange for Terzaghi to lecture before the civil engineering societies in Boston and New York. In November and December 1925, *Engineering News Record* published eight papers Terzaghi authored on the physical properties of clay and sand, as well as related topics. While some influential engineers were skeptical of his concepts, and sometimes offended by his arrogance, these papers and lectures helped establish Terzaghi's reputation.

One year after his arrival at MIT, Terzaghi was promoted to Associate Professor of Foundation Engineering. In the fourth and final year of his tenure at MIT, he was made full Professor. In 1929, somewhat unhappy with the resources provided by MIT, Terzaghi left the United States and took a position as Professor of Hydraulics at the Technical University in Vienna. MIT's loss would become Harvard's gain when Dr. Terzaghi returned to Cambridge a decade later. He died in Winchester, Massachusetts, on October 25, 1963.

Terzaghi's assistant during his first year at MIT was Glennon Gilboy, who had just received his B.S. degree in Civil Engineering from MIT in 1925. Born on September 11, 1902, in Duryea, Pennsylvania, Gilboy became a Research Associate in 1927. He would receive his M.S. and Sc.D. degrees from MIT in 1927 and 1928, respectively. His was the second doctoral degree in soil mechanics awarded at MIT. Gilboy became Assistant Professor of Soil Mechanics in 1929 and three years later he was appointed Associate Professor, a position he held until 1939. Prior to his departure, he was on leave of absence for two years on account of illness.

A brilliant researcher and teacher, Dr. Gilboy was known for his experimental and theoretical research on the design of hydraulic-fill dams and for the development of consolidation testing equipment and triaxial equipment. In 1935, he listed his principal subjects of research to be "physical properties of soils, foundations of buildings and bridges, and earth dams." Gilboy lived in Lincoln, Massachusetts, and had a consulting practice in the Boston area after he left MIT. He died on April 17, 1959.

In 1926, a young engineer named Arthur Casagrande joined Gilboy in assisting Terzaghi. Casagrande, born on August 28, 1902, in Haidenschaft, Austria, received a Diplom Ingenieur Degree in Civil Engineering from the Technical University in Vienna in 1924. After serving as an Assistant in Hydraulics at that university for two years, he came to the United States in April 1926. By December of that year, Terzaghi had arranged for Casagrande to be employed by the Bureau of Public Roads, serving as his assistant at MIT. He continued as a Research Assistant to Terzaghi until 1929 when he went to Vienna with Terzaghi to establish a soil mechanics laboratory. Following a year in Europe touring laboratories, Casagrande returned to MIT as a Research Assistant to Professor Gilboy.

In 1932, after making major contributions to the understanding of soil behavior and to the development of laboratory testing equipment and procedures, Casagrande moved to a lectureship position at Harvard University. Again, MIT's loss was Harvard's gain. The following year, with encouragement from his brother Leo, Arthur Casagrande received a Doctor of Engineering degree from the Technical University of Vienna based on his research and publications in the United States.

His promotion to Assistant Professor at Harvard came in 1934 and he ultimately became the Gordon McKay Professor of Soil Mechanics and Foundation Engineering. Dr. Arthur Casagrande died on September 6, 1981.

Dr. Leo Jurgenson, born most likely in Estonia in 1901, joined the MIT soil mechanics staff as a Research Associate in 1929 and remained in that position for five years. During his time in Cambridge, he was best known for his papers published in the *Journal of the Boston Society of Civil Engineers* in 1934 entitled, "The Application of Theories of Elasticity and Plasticity to Foundation Problems" and "The Shearing Resistance of Soils." He returned to Estonia where he died in Tallinn (then in the USSR) on September 7, 1986.

Arthur Casagrande's younger brother, Leo Casagrande, was born on September 17, 1903, in Haidenschaft, Austria. He attended the Technical University in Vienna and received a Diplom Ingenieur Degree in Civil Engineering in 1928. Following two years working as a structural designer in Germany, he came to MIT and from 1930 to 1932 he was a Research Assistant to Glennon Gilboy. The following year he was an assistant to Terzaghi at the Technical University in Vienna where he received a D.Sc. degree in 1933. Following employment in research positions in Germany and England, he returned to the United States in 1950 to begin a consulting practice. He lived in Winchester, Massachusetts.

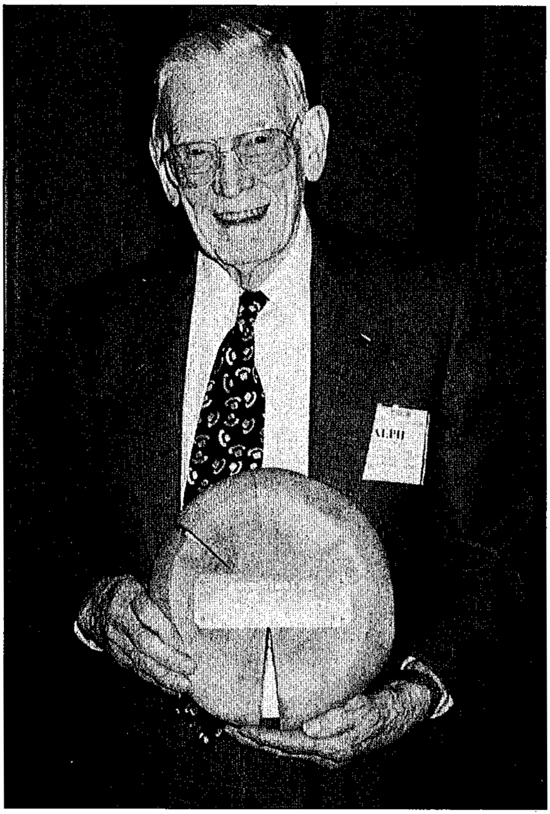
Dr. Leo Casagrande was best known for his research and practical applications of electro-osmosis for stabilizing soil in difficult foundation problems. From 1956 to 1972, he served as Professor of Soil Mechanics and Foundation Engineering at Harvard. Leo Casagrande continued a consulting practice with his son, Dirk, at Casagrande Consultants in Arlington, Massachusetts, until his death in Waltham, Massachusetts, on October 25, 1990.

In 1932, Donald Wood Taylor joined the civil engineering staff at MIT as a Research Assistant. Taylor was born in Worcester, Massachusetts, on December 2, 1900, and graduated from Worcester Polytechnic Institute with a B.S. degree in 1922. Before coming to MIT, he worked nine years for the United States Coast and Geodetic Survey and with the New England Power Association. In 1934, he became Research Associate at MIT and four years later, after the departure of Glennon Gilboy, Taylor was promoted to Assistant Professor. He received his S.M. degree from MIT in 1942 and became Associate Professor in 1944, a position he held until his untimely death in Arlington, Massachusetts, on December 24, 1955.

Professor Taylor was a quiet and modest man. He made major contributions to the fundamentals of shear strength of cohesive soils through direct shear and triaxial tests, to analyses of the stability of earth slopes and to our understanding of the behavior of clay during consolidation. In August 1942, MIT published *Research on Consolidation of Clays*, a comprehensive summary of his careful and detailed research during the prior six years.

Throughout his career, Taylor's work, whether in teaching, research or engineering, "was characterized by the highest professional standards, by great care and attention to accuracy, and by an allegiance to the scientific method in his quest for new knowledge. His high standards were as evident in his personal life as they were in his professional career. A man of utmost integrity,"[1] Taylor was guided "by a desire to meet problems and to treat people with fairness and full cooperation. His high character and scholarly attainments won him undeniable recognition in the field of soil mechanics, where he stood among the leaders of the century."[1] Unfortunately, MIT did not recognize his leadership in the discipline, having denied him promotion to full Professor before he died.

In 1948, Taylor published his book *Fundamentals of Soil Mechanics*. In the preface, he acknowledged the work of his predecessors, Terzaghi, Gilboy and Casagrande. In that same year, Terzaghi and Ralph B. Peck published *Soil Mechanics in Engineering Practice*, a book primarily dealing "with the art of getting satisfactory results in earthwork and foundation engineering at a reasonable cost." Both of these classic books were widely used in university courses in soil mechanics and foundation engineering. In addition, *Soil*



Ralph B. Peck.

Mechanics in Engineering Practice became an important reference for practicing geotechnical engineers.

Other members of the soil mechanics staff at MIT during the first 25 years through 1949 included:

- Harold A. Fidler, Research Assistant and Instructor from 1936 to 1940;
- Thomas M. Leps, Instructor from 1938 to 1939;
- Wilfred Merchant, Assistant from 1939 to 1940;
- William Enkeboll, Assistant from 1940 to 1941;
- John Lowe, Instructor from 1942 to 1945;
- Henry W. Wallace, Assistant from 1942 to 1943;
- T. William Lambe, who became an Instructor in 1945 and Assistant Professor in 1949;
- Victor F. B. DeMello, Research Associate from 1947 to 1949; and,
- Harl P. Aldrich, Jr., Assistant in 1947 and Instructor in 1949.

In addition to Gilboy, others who received doctoral degrees at MIT during the first 25 years after Terzaghi's arrival, in order of their award, included Alberto Ortenblad, Anant Pandya, Sidney Speil, Harold Fidler, Leopold Nieto-Casas, Shou-I Tsien, William Enkeboll, T. William Lambe and Victor F.B. DeMello.

By 1950, undergraduate and graduate courses in soil mechanics and foundations were well established at MIT and Harvard, as well as at most other engineering schools throughout the United States.

Terzaghi's Career at Harvard

By RALPH B. PECK, Professor Emeritus, University of Illinois, Urbana-Champaign, Illinois

When Terzaghi left for Vienna, he left behind Glennon Gilboy and Arthur Casagrande as his principal successors. Casagrande began to realize after a year or two that he was never going to be the number one man at MIT because he was second to Gilboy, who had a doctorate. A group of local engineers persuaded him that he might have an opportunity at Harvard because that school was reorganizing its engineering curricula. Harvard had decided to become essentially a graduate school in engineering; it closed down to a large extent the undergraduate school and intended to develop the graduate work. When Casagrande came back from Vienna after installing the laboratory for Terzaghi, he made contact with some of his friends who put in a good word for him and, fortunately, for Harvard and for soil mechanics, where he was able to establish a graduate program in soil mechanics.

The first year, 1932 to 1933, he had twelve students and during the second year, he again had a dozen students. In that second year, Terzaghi was interested in taking a sabbatical from Vienna; Casagrande persuaded him to consider coming to Harvard as a visiting professor or a visiting lecturer. Initially, Terzaghi decided to come for a year but he got side-tracked and only came for a half year, the last half of the 1935-1936 academic year. During the period that he was at Harvard, the class size increased to 29.

Casagrande proposed the idea of an international conference on soil mechanics. Terzaghi at first was a bit reluctant, perhaps because he felt the time was not right, but Casagrande persuaded him otherwise. And so the two began very actively to plan the First International Conference on Soil Mechanics and Foundation Engineering. Since Harvard was celebrating its 300th anniversary at that time Harvard's President Conant thought it would be appropriate to back it and put his full weight behind it.

Casagrande and Terzaghi spent considerable time not only discussing the structure of the conference, but also on who should be invited because there was a considerable field for selection. Both men felt there should be a considerable representation from practice, and there was probably much debate about the various individuals who should be asked. The final invited list included more practitioners than professors – not too surprising because there were not many professors in soil mechanics in those days. There were a number of people from Europe and people who had already expressed an interest in the development of the new subject.

The conference was certainly a major success, due in large part to the hard work of Casagrande and Phil Rutledge, who was his assistant at the time, but even more it was due to the several lectures that Terzaghi gave. He was the President of the conference, and he took his duties very seriously. His opening address to the conference is even now certainly required reading for anybody in soil mechanics. It set the tone for the new subject. The continued influence of Harvard was great, among other reasons, because it was the setting of that First International Conference.

Casagrande continued his teaching and research. The first class after the International Conference had some 29 students; then the enrollment dropped a little to 17 and rose again to 26. By 1938, with Casagrande's rising reputation and with his work with the U.S. Army Corps of Engineers, the enrollment jumped to about 42.

Actually, until 1937 I had not even heard of soil mechanics and was, therefore, a latecomer to the subject, but I was in that class of 1938. It was a large, very active and enthusiastic group. We all felt that we were at the very beginning of things and that we were embarking on a completely new venture in civil engineering, as indeed we were. John Watson was finishing his thesis on the triaxial testing of sands; Juul Hvorslev was in residence working on his tome on sampling; Bill Shannon was running the student laboratory; and Ralph Fadum was Casagrande's teaching assistant. Casagrande was consulting on the Fort Peck Dam after its failure and was very involved in designing the compensated foundation for the New England Mutual Life Insurance Building. It was indeed a busy time.

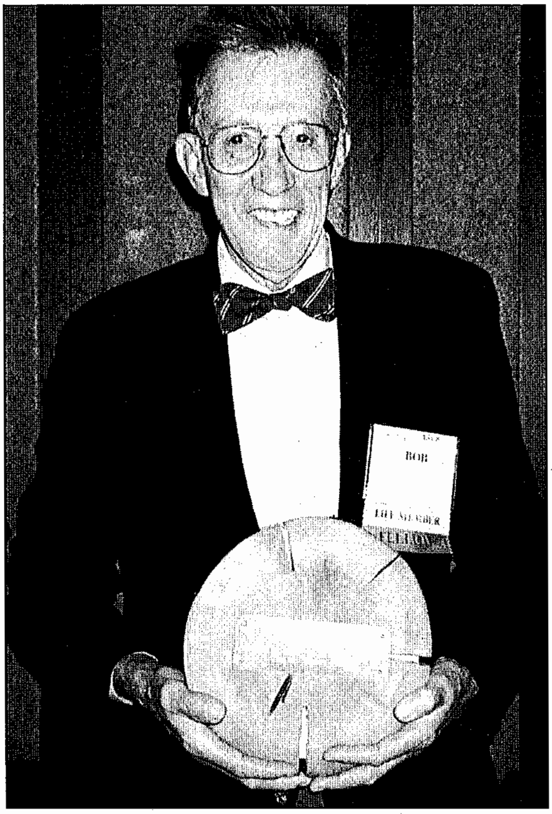
Evolution of Geotechnical Engineering at MIT: 1950–1998

By ROBERT V. WHITMAN, Professor Emeritus, Massachusetts Institute of Technology, Cambridge, Massachusetts

This period was one of intense effort in education and in research. Much of this research was inspired by the consulting activities of the faculty, and much also was fundamental in nature. Many different people were involved in the whole range of different aspects of what we now refer to as Geotechnical Engineering. A combination of theory, laboratory testing, field measurements and observations has been the trademark of the effort.

Table 1 (on page 42) summarizes the average number of geotechnical theses completed each year during different decades at MIT. Master of Science and Civil Engineer degrees are lumped together, as are Doctor of Science and Doctor of Philosophy degrees. By the way, there are no differences in the requirements for the two "types" of doctoral degrees; the choice is arbitrary and made by the candidate. It may be seen that the number of degrees peaked during the 1980s and has decreased during the 1990s. The records available to me for 1950 to 1995 list 570 theses in geotechnical engineering.

Table 2 gives a similar list concerning the size of the geotechnical faculty at MIT. Following the untimely death of Donald



Robert V. Whitman.

TABLE 1.
Number of Geotechnical Engineering Theses at MIT

	Average Theses/Year	
Decade	**SM/CE**	**PhD/ScD**
1950s	7	0.5
1960s	9	1.5
1970s	12	3.5
1980s	13.5	4
1990–1995	7	3

Taylor in 1955, T. William Lambe became head of what was called then the Soil Mechanics Division. Lambe, James Roberts, Charles Ladd and I formed the core of the division during the next several years. The number of faculty then rose gradually, reaching a high level by the latter part of the 1960s, and remained at essentially that level for nearly twenty years. The number has declined substantially since then. Table 3 lists all who have held a faculty appointment in the geotechnical program at MIT at the level of assistant professor or higher — totaling 24. Many remained for relatively few years before moving to other universities or into professional practice. Other faculty members from the Civil Engineering Department who contributed to the geotechnical program are listed separately at the end of the table.

In addition, many engineers holding positions as research associate, research engineer and lecturer have contributed mightily to the effort. Four names in particular stand out in my memory for their contributions. Robert Martin, starting with his work on clay mineralogy, was a major player in research and teaching during the first decades of this period; he continues to participate in today's work. Robert Schiffman dragged us somewhat reluctantly into the computer age. Some years ago Jack Germaine took over responsibility for the operation of the laboratories, including equipment development and training of student workers, and contributed to research studies as well, which continues today. Allen Marr played a major role during the days when the MIT group was especially active in field observations and the interpretation of results from these field programs. Doubtless there have been others deserving of special recognition as well.

Finally, up through 1995 there have been 21 people with the title of Visiting Professor, all of whom have expanded our perception of education, research and practice in geotechnical engineering. Of particular importance was Laurits Bjerrum, who spent several lengthy periods of time at MIT during the late 1950s and early 1960s. He was influential in shaping the efforts that evolved at MIT during that time, and ever since there has been a close association between MIT and the Norwegian Geotechnical Institute (NGI). One of MIT's proud accomplishments has been to help educate Kaare Hoeg and Suzanne Lacasse, both of whom followed Bjerrum as Directors of NGI.

All of these people have been pioneers to some degree. Space does not permit giving clear credit to their contributions in the following account of activities and contributions.

From the time T. William Lambe became head of the division until his retirement in 1982, he provided the enthusiasm and leadership that made possible this large and diverse effort. Lambe was particularly adept at convincing organizations, including consulting clients, to support the monitoring of and measurements on foundation and excavation projects. He even provided funding for the study and interpretation of the resulting data. His successes provided young faculty, and a generation of students, with practical experience, plus data and support for their research and theses. It was also Lambe who enticed Bjerrum to begin his association with MIT, and Terzaghi to present a series of lectures concerning some of his most challenging consulting projects. He also brought in other distinguished lecturers who provided a stimulated environment staff and students during the program's growth years of the 1950s and 1960s.

Lambe's first contribution was the publication in 1951 of *Soil Testing for Engineers*. At this time, he initiated studies of soil stabilization and clay mineralogy, working closely with Robert Martin and Alan Michaels. This research led to his involvement in the design and construction of earthen structures to retain liquid waste at a refinery in Venezuela to store oil. Donald Taylor had championed the stress path concept as a tool for guiding the analysis of strains within soil masses, and Lambe developed this tool further for the practical analysis of foundations and earth structures. He convinced the MIT administration to fund the monitoring and measurements of foundation movements at the numerous new buildings constructed on the campus during the 1960s — an effort known as FERMIT. A new tunnel for the Orange Line of Boston's rapid transit system was also monitored, and a large embankment over soft clay was studied in detail as it was loaded to failure. These latter efforts formed the basis for Prediction Symposia, where international experts were invited to predict what would happen before the actual results were revealed. And, finally, these efforts led to Lambe's formulation of the concept of "A, B, C predictions."

TABLE 2.
Average Annual Geotechnical Faculty at MIT

Year	Faculty Number
1950–1960	2–3
1964	7
1966	9
1967–1985	7–8
1985–1998	4–5

TABLE 3.
Geotechnical Engineering Specialists Holding Faculty Rank at MIT (1950–1999)

Harl P. Aldrich, Jr.	Philip M. Drinker	Ulrich Luscher
Amr S. Azzouz	Charles H. Downing	James E. Roberts
Mohsen M. Baligh	Herbert H. Einstein	Donald W. Taylor
Gregory B. Baecher	Ronald C. Hirschfeld	Erik H. Vanmarcke
Leslie G. Bromwell	Henry M. Horn	Robert V. Whitman
John T. Christian	Kaare Hoeg	Andrew J. Whittle
Patricia J. Culligan	Charles C. Ladd	Anwar E. Wissa
David J. D'Appolonia	T. William Lambe	Lyle A. Wolfskill

Others from MIT's Civil Engineering Department contributing to the geotechnical program include: C. Allin Cornell, Eduardo Kausel, José M. Roesset and Daniele Veneziano, as well as Alan Michaels, a Professor in Chemical Engineering.

I was brought aboard in 1951 to work on soil dynamics as it was applied to weapons effects. This was perhaps the nation's first large-scale program in soil dynamics. The project initially looked at the effects of very rapid straining on strength, building on earlier studies at Harvard. The study eventually shifted to pioneering studies of wave propagation through soil over a wide range of intensities of loading and then dealt with foundations for large radar towers. From the mid-1960s until my retirement in 1993, the emphasis was primarily in the area of earthquake engineering, including such topics as liquefaction, effects of local soil conditions on ground motions, soil-structure interaction and especially risk analysis and loss estimation. In cooperation with Cambridge University, I took some first steps in the use of centrifuged model testing for the study of geotechnical phenomena caused by earthquakes. During my first several decades, I also worked, with other faculty, on conventional geotechnical engineering problems. *Soil Mechanics*, authored by Lambe and myself, was published in 1969.

Donald Taylor's many years of study into the strength and deformation of clays were picked up and carried on by Charles Ladd, working together with various young faculty and laboratory directors. New laboratory equipment and testing procedures were developed, ranging from constant strain-rate consolidation tests to improved direct simple shear tests to triaxial testing with rotation of principal stress directions. Many carefully conducted tests were performed, together with detailed analysis of field observations. Many important contributions emerged from this effort. One example is the widely used SHANSEP approach for evaluating the strength of clays. Another was the now commonly used procedure of using x-rays to examine the uniformity of samples within sampling tubes.

In 1965, Ronald Hirschfeld joined the faculty to initiate a new thrust in engineering geology. After Hirschfeld left MIT to establish his engineering practice, Herbert Einstein carried on this work. Einstein made important contributions to landslide risk assessment in practice. He performed important basic research in rock mechanics, especially dealing with the process of fracture in rock and similar materials. He led the development of the MIT rock-tunneling model that combines information from exploration before and during tunneling with knowledge concerning tunneling practice and costs. This model has been used widely in practice. His ground-interaction model for tunnels is one of many innovations Einstein introduced into teaching.

At about that same time, John Christian began a second new thrust — in theoretical soil mechanics, including finite difference and finite element work. Mohsen Baligh, who developed the strain path method, continued this thrust. In the late 1960s, using this technique plus field tests, Baligh showed that excess pore pressures vary strongly near the tip of a penetrometer. These results provided the basis for the design of piezocones. The strain-path method has also been applied to understanding the normal and shear forces developed against driven piles. Today, Andrew Whittle carries on the theoretical thrust. Constitutive models for clay and sand have been developed, together with computer software, and applications have been made to foundations for offshore structures and to deep excavations.

Probabilistic geotechnical engineering was still another new thrust, beginning in the early 1970s, as represented by the contributions of Erik Vanmarcke and Greg Baecher. Their work has been applied to problems in site exploration planning and to the stability of embankments. I have continued to have an intense interest in risk analysis, especially as applied to earthquake problems.

More recently, Patricia Culligan has established work in geo-environmental engineering. Among other efforts, she has been using centrifuged models to study the efficiency of remediation techniques.

Additional less major efforts also come to mind: behavior of lunar soil, residual strength of over-consolidated clays and shales, and early interactive computer programs for slope stability and consolidation. There are others as well, not to mention the many important contributions of the staff through consultation on significant national and international projects. Not without undue modesty, it has been a remarkable and productive five decades.

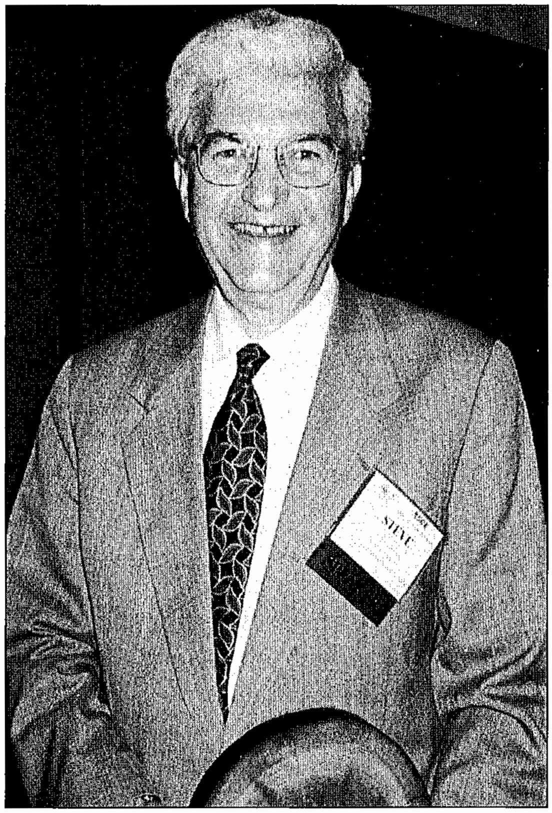
Arthur Casagrande at Harvard, 1932–1981

By STEVE J. POULOS, founding Principal, GEI Consultants, Inc., Winchester, Massachusetts

Arthur Casagrande was indeed a pioneer in the field of soil mechanics. It was largely through his efforts that soil mechanics became a profession and a distinct discipline within Civil Engineering.

At Harvard in 1932, Casagrande continued the research he had started at MIT. He went on to study seepage through soils. This research led to the rational design of embankment dams for control of seepage. During the mid-1930s and early 1940s, Casagrande developed and expanded concepts on the shear strength of soils. He developed the first understanding of liquefaction. He clarified how triaxial tests should be performed to measure shear strength for stability analysis, and developed and improved almost every aspect of soil testing. He introduced the concept of maximum past pressure and over-consolidation in clays. Starting in 1946, Casagrande carried out the first dynamic testing of soils in connection with studies for a sea-level canal to replace the Panama Canal. He also investigated the swelling characteristics of clays and the effects of long-time loading on the strength of clays. In the 1950s and 1960s, he introduced the idea of cracking of earth dams and investigated the topic. His research focused on the strength and deformability of compacted soils due to their importance for the design of earth dams. In short, he investigated nearly every test for measuring the index and engineering properties of soils (see Table 4).

Casagrande's contributions placed him in a good position to initiate and organize the First International Conference on Soil Mechanics and Foundation Engineering at Harvard in 1936. Approximately 100 individuals working in this new field attended. Karl Terzaghi accepted the presidency of the conference. The list of attendees attested to the importance of this conference.



Steve J. Poulos.

Casagrande reviewed every conference paper and prepared the three-volume proceedings almost single-handedly. The conference was a great success and fourteen international conferences have been held to date at locations throughout the world. In effect, the 1936 conference was the beginning of the professional field of Soil Mechanics.

When Karl Terzaghi decided to leave his post at the Technical University of Vienna, he sought a position in the United States. Casagrande convinced Harvard to offer him a professorship. After World War II, Harvard also offered a professorship to Leo Casagrande. These three individuals at Harvard formed a unique core for teaching soil mechanics.

Arthur Casagrande was consultant to the U.S. Army Corps of Engineers from the mid-1930s to the end of his career. He helped the Waterways Experiment Station develop its research program in soil mechanics. He consulted on hundreds of dams, buildings and other structures for public agencies and pri-

TABLE 4.
Research Contributions by Arthur Casagrande

Hydrometer analysis
Atterberg limits (liquid limit device)
Classification & identification of soils
Frost action in situ (first cold room)
Use of undisturbed samples
Pore pressures during shear
Maximum past pressure
Triaxial text development for soils
Direct shear test
Flow net sketching
Analysis of seepage through dams
Liquefaction ("critical density")
Undrained, consolidated undrained & drained tests
Permeability testing
Base course drainage
Piezometers
Stability analysis
Piping in dams
Undisturbed sampling
Cracking of earth dams
Dynamic testing of clay-shales
Long-time strength of soils
Dilative/contractive behavior
Swelling of clays
Compaction
Stress-strain of compacted soils

vate companies throughout the Western hemisphere. His word was often final when difficult judgments were being made. These projects were wonderful sources of funds for his students. Casagrande's consulting work led him to chair the committee to create a new Boston Building Code in 1948. That code formed the basis of the one now used by the Commonwealth of Massachusetts.

The U.S. Army Corps of Engineers asked Casagrande to make a trip to Fort Peck Dam to evaluate the partial failure of that dam during its construction. The train ride to North Dakota was one week long, during which he read all of the material about the dam and planned his work. He spent one week evaluating the dam and collecting data. On the week-long train ride home, he wrote the report. Upon his arrival, he sent the final report to the U.S. Army Corps of Engineers.

However, Arthur Casagrande is perhaps best known for his role as Professor of Soil Mechanics at Harvard. He started teaching soil mechanics at Harvard in 1932, much as he and others had done at MIT. In 1933, he added a course on soil testing. In 1935, he started a course on Seepage through Soils. In 1939, several of his students banded together to produce his *Notes on Soil Mechanics*. Casagrande, in spite of all his contributions, never wrote a book himself. Later, courses in Engineering Geology and Applied Soil Mechanics were added and were taught by Karl Terzaghi, Leo Casagrande and Ruth Terzaghi.

He and his assistants at Harvard (Ralph Fadum, Stanley Wilson, Jose Corso, Ronald Hirschfeld, Walter Ferris and myself) taught about 1,200 graduate students, which included doctorate degrees to 20 individuals.

Casagrande once sent a student to cut and retrieve two block samples of varved clay from the Connecticut River Valley. The student did not have a car or money, so Casagrande gave the student his car and some money. The student returned with two blocks of clay in the trunk of the car. Each block weighed about 200 pounds. The springs of the car were destroyed during this trip, being overloaded with the clay. Casagrande was not happy. Casagrande cut a piece of the varved clay from the Connecticut River Valley into the shape of a chocolate bar. The clay was a milk chocolate color and he gave it to a student in the front row of his class. The student, thinking it was a candy bar, took a bite. After that, students did not sit in the front row of his class.

During World War II, Casagrande taught soil mechanics to about 400 army officers on topics that related to the rapid construction of military airfields. He taught about classification and identification of soils, compaction and base course drainage. He developed much of the information that he presented.

In 1963, he introduced the Special Program on Soil Mechanics, which enabled experienced engineers to take all of the graduate soil mechanics courses at Harvard in one concentrated semester. The program drew engineers from government organizations and some from private firms. About 150 students, ranging in ages from 22 to 65, entered the program from 1963 to 1969.

Arthur Casagrande was an outstanding teacher. He inspired his students with a love of learning and respect for facts. A sampling of some of the names of his students during the period 1934 through 1955 is shown in Table 5; many of these names are easily recognizable.

Casagrande received several prizes for his publications, was invited to give many honorary lectures, was awarded two honorary doctorate degrees and received the Distinguished Civilian Service award of the U.S. Army. He was elected to the National Academy of Engineering.

Casagrande loved to teach. Through it all, he taught his own courses by himself, getting assistance only to grade papers and prepare demonstrations. We all learned and benefited a great deal from Arthur Casagrande as a primary pioneer in soil mechanics.

TABLE 5.
Some Students of Arthur Casagrande (1934–1955)

Philip Rutledge	Jack Hilf
Earle Littleton	Stanley Giziensky
Ralph Fadum	James Gould
J.O. Osterberg	Charles Ripley
William Shannon	Milton Vargas
Harry Cedergren	John Focht
Ralph Peck	Martin Kapp
George Bertram	Richard Loughney
William Swiger	George Sowers
Thomas Leps	Stanley Wilson
J.B. Eustis	Othar Zaldastani
James Haley	Harl Aldrich (MIT)
Robert Hardy	Harry Seed
Philip Keene	James Sherard
Nabor Carillo	Ronald Hirschfeld
John Lowe	James Mitchell (MIT)
Charles Mansur	William Wahler
Malcolm Pirnie	James Parcher
Ernest Spencer	Norbert Schmidt

Note: A complete list of students is presented on pages 419 to 431 of the *Casagrande Volume, Embankment-Dam Engineering,* edited by Ronald C. Hirschfeld & Steve J. Poulos (John Wiley & Sons, 1973).

Summary Comments

By RONALD C. HIRSCHFELD, Moderator

Only three students received doctorate degrees under Karl Terzaghi in the United States: Alberto Grtenblad and Glennon Gilboy at MIT, and James Sherard at Harvard. Sherard spent most of his research time with the Bureau of Reclamation. His final oral exam was memorable. Sherard had done his work very independently and had written monthly reports to Terzaghi. Sherard concluded that Terzaghi never read them. Sherard put what he thought was a brilliant idea in one of his monthly reports, and Terzaghi never responded to it. Once, when Sherard came back for a six-month visit, he and Terzaghi were talking in Terzaghi's office. This same idea came into Terzaghi's mind and Terzaghi started putting it forth as his own idea.

When Sherard gave the final defense of this thesis, Terzaghi asked a very difficult question. Sherard responded, "That is a very difficult question, Professor Terzaghi." Terzaghi replied, "If I had known the answer, I would not have asked the question." Terzaghi and Casagrande got into a rather heated argument about the definition of factor of safety. Sherard watched the argument going back and forth. He said afterward he did not know who was being examined.

Response to an Audience Question

Audience: Dr. Peck, please tell us about the first time you met Dr. Terzaghi.

Dr. Peck: Terzaghi had come from Europe and he was installed in a small office. We did not see much of him. He gave two lectures, as I recall; they were about Rankine's theory. Arthur Casagrande had just finished telling us that Rankine's theory was out of date and not very useful, so we were not quite sure why he gave those lectures (how he used Rankine's theory later became apparent in *Theoretical Soil*

Mechanics, Chapter III and *Soil Mechanics in Engineering Practice,* Art. 28). One day Ralph Fadum called me in and said that Dr. Terzaghi was working on a book. He wanted to say something about grain-size analysis, perhaps by representing grain size in a statistical way. He said that Terzaghi knew statistics but was not sure of the English terms for statistical parameters.

All of us at Harvard had sat in on Gordon Fair's course in statistics, because it was a remarkable course and he was a very good lecturer. We did not want to take his courses in sanitary engineering, but we could take statistics. So, Fadum asked if I would go up and talk to Terzaghi and help him. I thought this was nice; the great man had just been here about two weeks. I went to his office; he wrote down some formulas, asked me what we called the terms; that is how we worked. I was pleased to have had about 45 minutes with the great man and to have survived both him and the cigar smoke. I felt as if I had the edge on the rest of the students. Two weeks later, I was in Chicago working as Terzaghi's representative on the construction of the city's subway.

ACKNOWLDEGMENTS — *The authors wish to acknowledge the support and guidance provided by Ronald Hirschfeld and Charles Ladd of MIT in the preparation of the panel discussion. Ronald Hirschfeld developed the topics for each speaker and moderated the panel discussion.*

IN MEMORIAM — *Dr. Ronald C. Hirschfeld passed away on March 7, 2001, after being stricken by a sudden illness while teaching a class. We lost a great leader, friend and mentor, as well as a significant connection to the pioneers in soil mechanics. He provided inspiration and guidance for so many in the BSCES community, and worldwide throughout the geotechnical engineering profession.*

ANNI H. AUTIO, *P.E., is a senior civil/environmental engineer employed by CDM Federal Programs Corporation in Cambridge, Massachusetts. She has over 19 years of experience in regulatory compliance and remediation. She holds a B.S. in Civil Engineering and an M.S. in Environmental Engineering from Worcester Polytechnic Institute. She was the past President of the BSCES at the time of this panel discussion, and serves as chair of the Section's History & Heritage and Library Committees. She also served as Secretary of The Engineering Center Board of Directors in Boston from 1998 to 2000.*

MICHAEL A. MCCAFFREY, *P.E., is a geotechnical engineer and Associate at GEI Consultants, Inc., in Winchester, Massachusetts. He received a B.S. degree from Michigan Technological University in 1978 and an M.S. degree from Cornell University in 1984 in Geotechnical Engineering. He was the BSCES Geotechnical Group Chairman at the time of this panel discussion.*

REFERENCE

1. Memoir on Donald W. Taylor, *Journal of the Boston Society of Civil Engineers,* Vol. 43, No. 2, April 1956.

George Washington, Engineer

First published in 1932, this narrative recounts our first President's background and achievements as an engineer, surveyor, agriculturalist and land developer.

EDWARD GROSSMAN

One side of George Washington's career has been sadly neglected by his biographers. Our first President was professionally, and also by aptitude, an engineer. The neglect of this phase of his interesting life is due not so much to lack of interest as to ignorance. Of the five hundred (more or less) biographies of Washington, not one has been written by an author capable of appreciating the significance of his early career and able to reconcile it with his later work.

George Washington wrote voluminously. He left us diaries, copies of letters, journals and ledgers written during his lifetime. Professor Jared Sparks, who first collected Washington's writings (1837), attached little importance to his early journals and diaries. His lead was followed by the later biographers. They did attach importance to his "godlike calm" in the face of disorder, and to his extreme probity. These were the outstanding traits of his character. These were due, of course, to a habit of clear thinking and ability to be honest with one's self. And perhaps his attitude of mind had something to do with it. He was primarily an engineer with a thorough grasp of essentials. Side issues did not matter. This trait made him see political issues in a broad and impersonal way — not a popularizing trait, of course, but conducive to the benefit of the country as a whole. Thus, when the French Revolution broke out, and the notorious "Citizen" Genêt came over here to enlist sympathy, President Washington was almost the only one who did not lose his head. Nearly all his countrymen were clamoring to "pay our debt to France" and help her fight all Europe. The President alone saw the disadvantage of such a course and had Genêt recalled.

Washington alone remembered that it was the French King who, because of hatred for England, helped the Americans. The French people had no more to do with the desire to help the Americans than the Hessians, who were hired out by their masters to fight the colonies.

He was also a great military strategist. If it were not for him we would not be American citizens. The study of this phase of his career is productive of material enough to fill two

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London: Printed for S. Clarke, the corner of Exchange Alley, next Birchin Lane 1727.

books. We will not dwell upon it, except to state that he conducted the Revolutionary War as a problem in engineering. Certain "key battles" had to be won. In these he was victorious. The British won, time after time, sometimes seriously crippling the American army, yet Washington was victor, because his engineering sense taught him to pick only essentials. The British commanders did not have that attitude of mind and lost the war for their King, although they won more battles for him.

He was the first agricultural engineer in the country. He designed and built his own buildings, devised agricultural implements and conducted an experiment station.

He was the pre-eminent land developer of his time, forever trying to develop the western part of the country, forming development companies, improving communications and settling people on the land.

All that will, however, be told in its turn.

Early Background

George Washington was born on February 22 (new style), 1732, in Westmoreland County, Virginia. His father was Augustine Washington, and his mother Mary (Ball) Washington, who was Augustine's second wife. George was the eldest son of this marriage. Not long after George's birth the family moved to Stafford County on the east side of the Rappahannock River opposite Fredericksburg. There the elder Washington died at the age of forty-nine on April 12, 1743. Augustine Washington had been a thrifty planter and left his family in comfortable circumstances.

To each of his children he bequeathed an estate ranging in size from 2,500 acres, which was Lawrence's portion (he was the eldest), to the 600- or 700-acre tracts left for the younger boys. The mother was left in full charge until the respective heirs came of age.

When George was of proper age he was sent to school. In those days schools were kept for the purpose of teaching only the essentials. The real education was obtained usually in England at public schools and universities. The schools in Virginia at the time were kept by itinerant schoolmasters, parsons and the like.

George's first teacher was a Mr. Hobby, a former indentured servant and tenant on the

Washington estates. Besides his occupations of sexton and occasional farmer, Mr. Hobby was also a schoolmaster, but he could not teach George very much. The latter was then sent to Mr. Williams's school, where he received a severely practical drilling in the execution of business forms, a smattering of miscellaneous education and a great deal of mathematics. Of that Mr. Williams gave as much as the pupil desired.

Although George was a fairly apt pupil in the ordinary course of English and business forms, his greatest delights began when Mr. Williams led him through the mazes of geometry, trigonometry and surveying. He actually loved mathematics, and the more his teacher gave him, the more he desired.

The textbook used by Mr. Williams was the then popular *vade mecum* (see sidebar on the previous page). This book George studied over and over again. From it he completed his education in "Arithmetick," and learned geometry, surveying, farming, medicine and all the other good things promised on the title-page. From the lessons learned in its pages he earned his living during his professional career as a surveyor. He learned how to be methodical and precise, and to think clearly.

The following extracts from the twenty-fourth (1750) edition of this work will no doubt be of interest:

> *Of Surveying, or measuring Land.* Note, that 16 Feet and an half make a Pole or Perch; 160 Square Poles, or 4 Roods, make an Acre of Land; 40 Poles make a Furlong, 8 Furlongs, or 17 yards, make a Mile.
>
> Land is generally measured by a Chain of 4 equal Parts, or Links, 25 of which are a just Pole, or Perch; consequently, 10 square Chains, or 100,000 Links, make an Acre of Land. But though this Chain, called Gunter's Chain, from its Inventor, be commonly used, yet Land may be measured by a Cart-Rope, or a common Pole, 16 Feet and an Half in Length:
>
> *How to measure Land by Gunter's Chain.* We have already observed that this Chain is 4 Poles in Length, or 22 Yards, which is 66 Feet, or 792 Inches; it is divided into 100 Links, at every 10 Links is a Brass Ring, for the more ready counting it in Measuring, so that it is no matter which End goes foremost; and he who draws it should carry in his Hand 10 small Sticks, to stick in the Earth at every Chain's Length, and he who follows the Chain to gather up the Sticks.

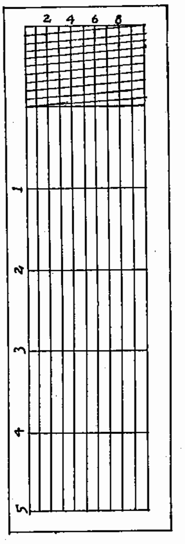


FIGURE 1. Diagonal scale.

> *A Description of the Diagonal Scale, very useful in plotting, &c. Land.* [See Figure 1.] This Scale consists of 11 parallel Lines, equi-distant from one another, so as to include 10 equal Spaces, which are cut by perpendicular Lines, dividing the Scale into equal Parts numbered 1, 2, 3, 4, 5. One of these Divisions, viz. the last on the Right hand, is subdivided by diagonal Lines; so that if one of the Large Divisions represent Chains, a Line may be measured to a single Link, one of the large Divisions being subdivided by the diagonal Lines into 100 equal Parts, the Number of Links in a Chain; and, consequently, any Number of Chains of Links may be set off by this Scale. A little Consideration of the Figure will sufficiently explain its Nature, and render its Use very easy and expeditious. If one of the large Divisions are reckoned 10 Chains, then every one of the smaller Divisions will be 100 Links, and consequently you can only measure within 10 Links of the Truth,

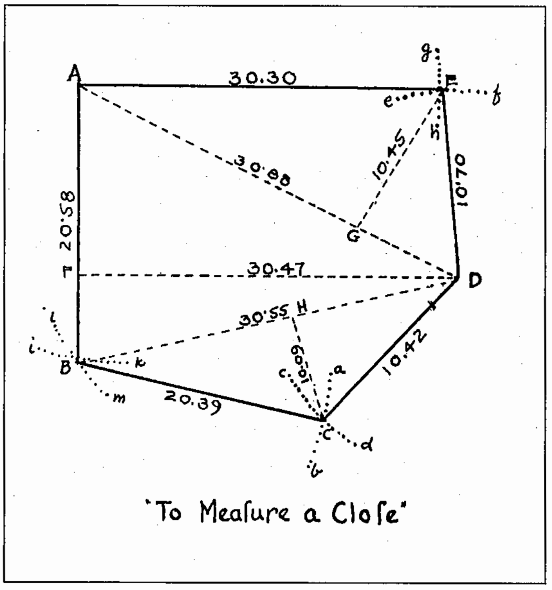


FIGURE 2. Diagram used to measure a field.

every smaller Division, which signifies 100 Links, being subdivided by the diagonal Lines into 10 Parts only. But the Practitioner should always remember to make Use of as large a Scale as possible, especially if he would have his Work exact, and always to reckon one of the large Divisions one Chain only, as the Dimensions of any Field or Parcel of Land may then be plotted with the greatest Accuracy.

To measure a Close or Field by the Chain, plot it on Paper, and find it's Content. [See Figure 2.] Let ABCDE represent the Close or Field to be measured and plotted by the Chain only. In order to do this I begin at the Corner A, and measuring in a straight Line to the Corner D, which I find 30 Chains, 88 Links, and note it down in my Paper. Then I measure along the Side of the Hedge from D to E and find it 10 Chains 70 Links, which I also note down. From thence I measure along the Side of the Fence from E to A, and having found it 30 Chains 30 Links, I note it down; and proceed in my measuring from A to B, which I find 20 Chains 58 Links. From the Corner B I measure to the Corner D, and find it 30 Chains 55 Links. From D I measure to the Corner C, and find it 10 Chains 48 Links: And from C to B 20 Chains 39 Links. Then I have taken all the requisite Dimensions. The next Operation is

To Plot the above Field on Paper. In order to [do] this I draw a Line from A, representing my first Station, of a sufficient Length, and take from my diagonal Scale 30 Chains 88 Links, and placing one Foot of the Compasses in the Point A, set off the Distance to D, which will represent the Corner of the Field I measured to from A. Then I take from my Scale 10 Chains 70 Links, and setting one Foot of the Compasses in D, describe the small Arch *ef*. I also take from the same scale 30 Chains 30 Links, and placing the Point of the Compasses in A, describe with the other the small Arch *gh*, cutting the former in E; and draw the Lines ED and EA. Then I take from Scale 20 Chains 58 Links, and setting one Foot of the Compasses in A, and with the other describe the small Arch *ik*. I also take 30 Chains 55 Links from my Scale, and setting one Foot of the Compasses in D, with the other sweep the small Arch *lm*, cutting the former in B; and draw the Line AB, and the dotted Line BD. Lastly I take 20.39 from my Scale, and from B sweep the same Arch *ab*; and with 10.48 sweep, from D, the small Arch *cd*, cutting the former in C; and draw the Lines BC and DC. Thus is the Plot finished; and every Part of it may be measured by applying it to the same Scale. Nothing now remains but

To find the Content of the Field. The Field is divided by the dotted Lines AD and BD into three Triangles, ADE, ABD, and BCD, and consequently, the Contents of these three Triangles when added together will give the Content of the whole Field: But before these Contents can be found, the Lengths of the Perpendiculars EG, DF, and CD must be measured in the following Manner: Place one Foot of the Compasses in E, and extend the other until it will just touch the Line AD, but not cut it, and measure the Distance between the Points of the Compasses on the Scale, 10 Chains 45 Links. Do the same by the Perpendiculars DF and CH, and you will find the former 30.47 and the latter 10.9 [10.09?]. Having thus found the Lengths of the three

Perpendiculars, the Areas of the three Triangles will be easily found by the Rule laid down for finding the Content of a Triangle, in the Article of Measuring Superficies.

For the Triangle ADE,

	3088	Length of the Base
	522	Half the Perpend.
	6176	
	6176	
	15440	
	1611936	

For the Triangle ABD

	2058	Base
	1523	Half Perpend.
	6174	
	4116	
	10290	
	2058	
	3134334	

For the Triangle BCD

	3055	Base
	504	Half Perpend.
	12220	
	152750	
	1539720	

	1611936	1st Triangle
	3134334	2nd Triangle
	1539720	3rd Triangle
Acres	62.85990	
	4	
Roods	3.43960	
	40	
Perches	13.38400	

Thus the Area of the Field is 62 Acres, 3 Roods, and 13 Perches.

Of course, this "course" in surveying was quite meager. Mr. Williams, pleased at the young fellow's desire to learn, helped him out by explaining the use of the surveyor's compass (the transit instrument was a later invention), and encouraged his practicing the art until he was quite proficient.

Young George definitely decided he would like to be a surveyor, and in order to fit himself more thoroughly for his profession he used to run practice surveys in the neighborhood, thus making sure of digesting the teachings of *The Young Man's Companion* and of Mr. Williams. One of his practice surveys is that of Lawrence Washington's turnip field (see Figure 3). A sample set of field notes is the following:

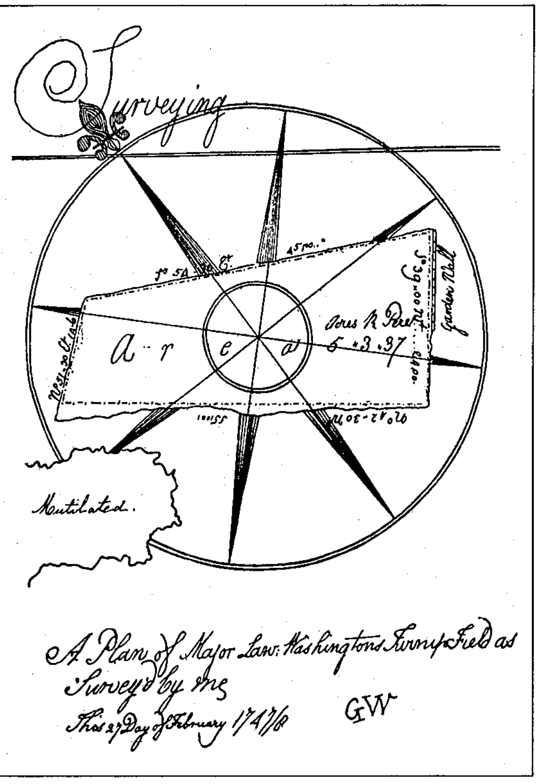


FIGURE 3. Lawrence Washington's turnip field.

> August 18th 1747[.] Then survey'd the following Piece of Land at one Station in the School House old field bounded as pr field Book. Vizt Beginning near a Persimon within ye field Extending thence to a Fence Stake S 15-00 E 165°,, 00′-28 Pole thence S 19-00 W 199°-00′-27.5 Pole thence S 47 W 227° -00′ 18.9 thence S 76-00 W 256°-00′-21.4 thence N 42 W 318°-00′-46.3 thence N 29-00 E 29°-00′-34 Pole.

But let us not laugh at this casual preparation for an engineering career. Organized engineering curricula are of comparatively recent origin.

Of his notes kept at this period one of the most interesting is one copied from those of a survey by James Genn. The notes are as follows, the plat being Figure 4:

The Mannor how to Draw up a Return when Survey'd for His Lordship or any of y^e Family.

March y^e 15th 1747–8

Then Survey'd for George Fairfax Esqr. Three Thousand & twenty Three Acres of Land lying in Frederick County on Long Marsh Joyning Thomas Johnstones Land and bounded as follows

Beginning at (A) Three Hickorys Corner Trees to Thomas Johnstones Land & Extending thence along his S 13 W^t One hundred Seventy two Poles to (B) a Locust Johnstones Corner thence along another of his Lines 5 34 E^t 150 po. to (C) a White Oak another of his Corners thence S° 75 E^t 186 po & to (D) a large Hickory thence N° 58 E^t 160 po xing [crossing] a Spring Run to (E) three Red Oak Fx on a Ridge thence N° 30 E^t 436 po to a Hickory an Red Oak Fx at (F) thence N° 60° W^t 90 po to (G) a Large White Oak Fx thence No 7 Et 420 po xing Long Marsh to (H) two Red Oaks and a W: O: Fx in a Bottom in y^e afores^d Thomas Johnstones line finally along his line S° 80 E^t one Hundred fourteen Poles to Ye Beginning Containing Three Thousand & twenty three Acres.

p^r James Genn
Henry Ashby
Richard Taylor — *Chain Men*
Robert Ashby — *Marker*
W^m Lindsey — *Pilot*

N. B. The Distances in y^e above Writing ought to be Written in Letters not in figures only I have done it now for Brevity sake.

Other early surveys are illustrated by Figures 5 and 6, showing the country about Mount Vernon house and Hell Hole, respectively. Figure 7 (on page 56) shows another view of the area.

At an early age he thus learned to be methodical. All his affairs were attended to systematically, and full records were kept.

According to Sparks, Washington not only was able to use logarithms in making his calculations, but apparently got up a system of statistical mathematics for himself. On every occasion he reduced information to

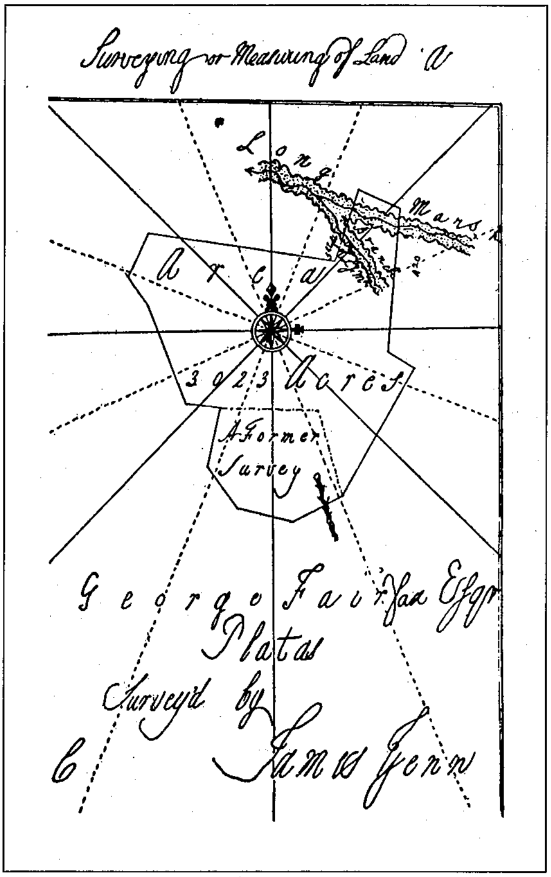


FIGURE 4. A study illustrating "The Mannor how to Draw up. . ."

graphs and tables for the better digestion of the facts:

The constructing of tables, diagrams, and other figures. . . was an exercise in which he seems at all times to have taken much delight. . .

While at the head of the army this habit was of especial service to him. The names and the rank of the officers, the returns of the adjutants, commissaries, and quartermasters were compressed by him into systematic tables, so contrived as to fix strongly in his mind the most essential parts, without being encumbered with details. When the army was to. . . perform any movement. . . a scheme was first delineated; and at the beginning of an active campaign. . . the line of battle was projected and sketched on paper, each officer being assigned to his

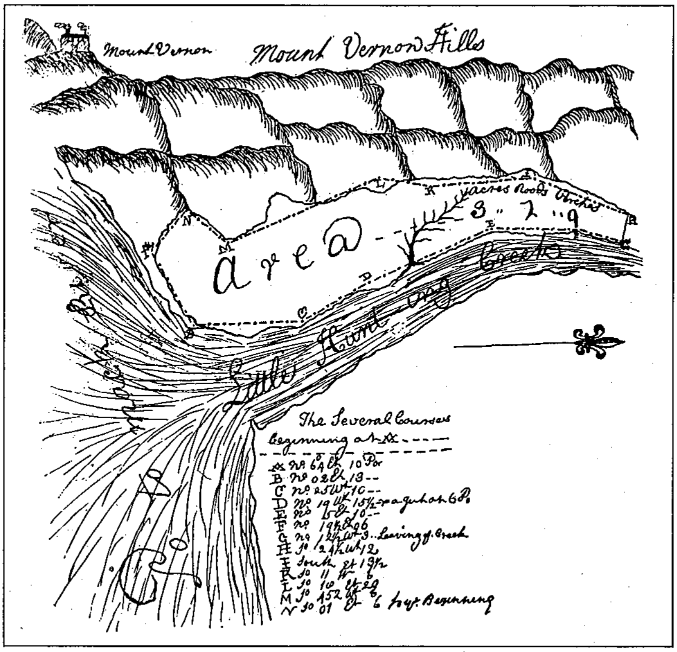


FIGURE 5. Mount Vernon Hills, 1747 (traced from original).

post, with the names of the regiments and strength of the forces he was to command. [An example of this is Figure 8 on page 56.]

During the presidency it was likewise his custom to subject the treasury reports and accompanying documents to the process of tabular condensation. . . it enabled him to grasp and retain in their order a series of isolated facts, and the results of a complicated mass of figures, which could never have been mastered so effectually by any other mode of approaching them. Such were some of the benefits of those parts of his education, to which he was led by the natural bent of his mind.

But the future President was not a "grind" during his boyhood. His leisure moments he filled with manly sports. There was not a better or a more daring horseman than this tall, husky boy of fifteen who was well to the fore in every fox hunt. He could wrestle with the best of his companions, and as a drillmaster in the mimic warfare which the boys of that day effected he was an acknowledged expert. Withal, George had a reputation for probity which caused all disputes to be left to his arbitration, and no objection was ever made against his decisions.

He had now become almost sixteen years of age. His boyhood was over. Now he was to take his place among men.

He had taken full advantage of his education and had become a competent surveyor as far as theory was concerned. All he needed was practice, and that was soon forthcoming.

Early Career

Lord Fairfax, a neighbor to the Washingtons, was an elderly and affluent bachelor, who, having visited Virginia, forsook his native England and came to live in the New World. He was an enthusiastic huntsman, as was young Washington, and thus they were brought constantly together.

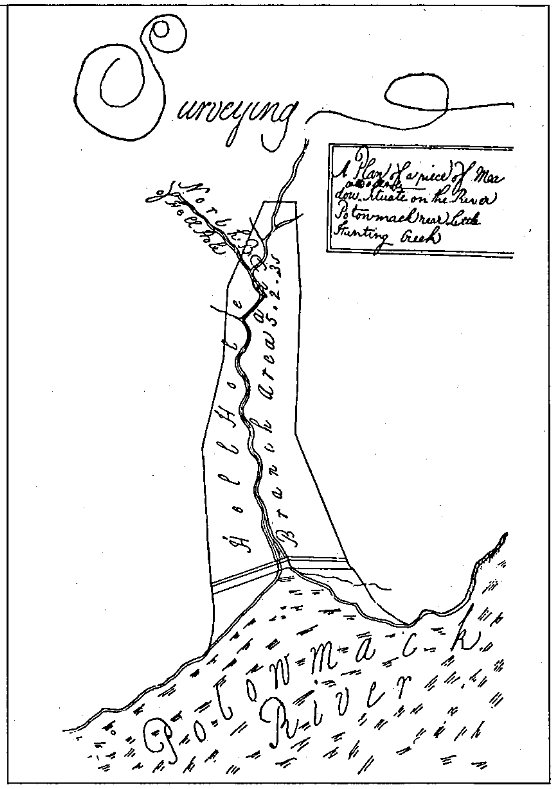


FIGURE 6. Survey of land known as Hell Hole.

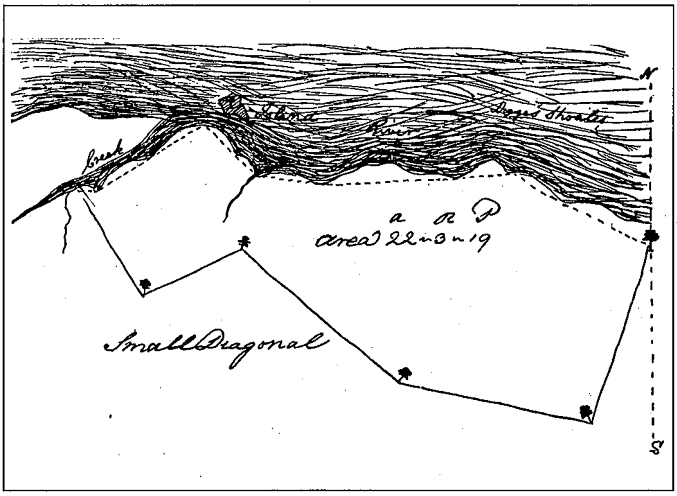


FIGURE 7. Survey of land known as Hell Hole.

Lord Fairfax owned a huge grant of land on the other side of the Allegheny Mountains. This had never yet been surveyed, nor, indeed, been looked after in any way at all. His Lordship decided to survey the land, divide it into lots, and discourage the squatters who were making free there. To George Washington he offered the job of surveyor. Needless to say, the offer was quickly accepted. Preparations were speedily completed, and the party, consisting of George Washington, George Fairfax, a nephew of Lord Fairfax, and some assistants, started out. At Mr. Neville's, in Prince William County, Mr. James Genn, a licensed surveyor, joined them.

It was while on this trip that young Washington first began keeping his diaries, which are now of great historical value. We have room for only a few selections:

Fryday, March 11th 1747–8. Began my Journey in Company with George Fairfax, Esqr.; we travell'd this day 40 miles to Mr George Neavels in Prince William County.

The double dating of the year was due to the following reason: January 1 was accepted as the beginning of the historical year, while March 25 was held by some to be the

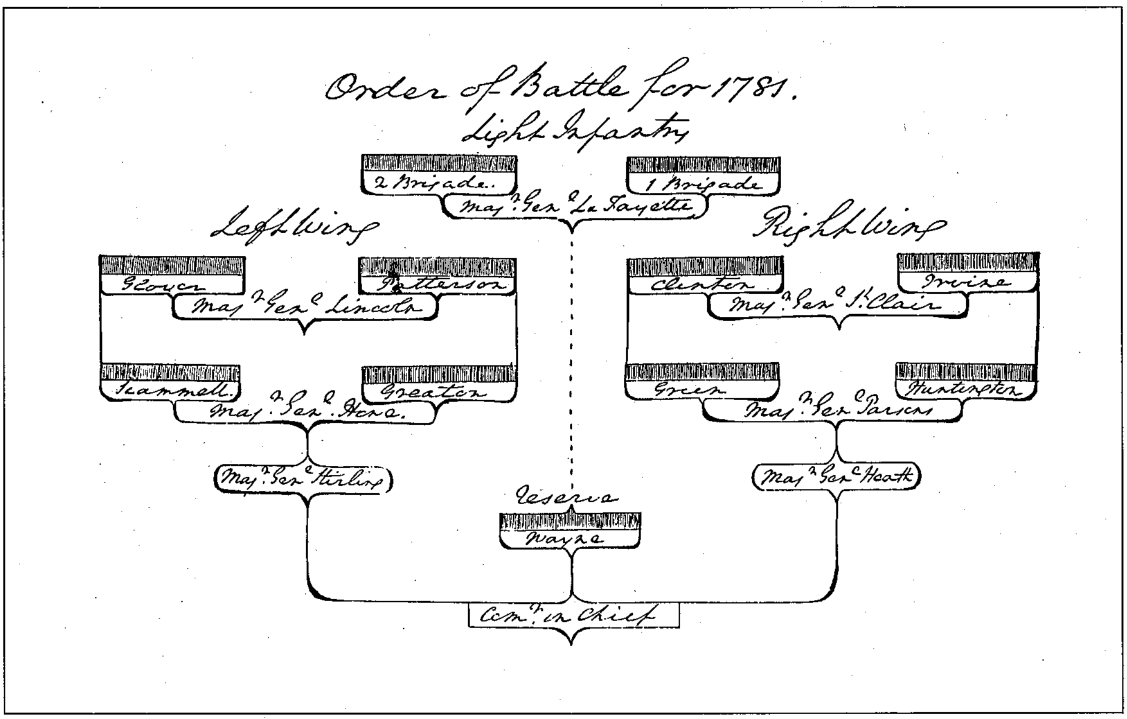


FIGURE 8. An order of battle for 1781.

beginning of the civil or legal year. Double dating was used between January 1 and March 25 of the year, the single date being used the rest of the year. When the Gregorian (new style) calendar was adopted by Britain in 1752 this double dating stopped. The year of this Journal is 1748:

Saturday March 12th this morning Mr James Genn ye surveyor came to us, we travell'd over ye Blue Ridge to Capt Ashbys on Shannondoah River, Nothing remarkable happened.

Monday 14th We sent our Baggage to Capt Hites (near Frederick Town) went ourselves down ye River about 16 Miles to Capt Isaac Penningtons (the Land exceeding Rich & Fertile and all ye way produces abundance of Grain Hemp Tobacco &ca) in order to lay of some Lands on Cates Marsh & Long Marsh.

Work was started promptly the same day, as is testified by the following field notes:

March y. 15th 1747-8. Survey'd for George Fairfax Esqr. a Tract of Land lying on Cates Marsh and Long Marsh beginning on three Red Oaks Fx on a ridge the N° Side a Spring Branch being corner to ye 623 Acre Tract & Extending thence N° 30° Et 436 poles to a Large Hickory and Red Oak Fx near John Cozines House thence N° 60° Wt 90 poles to a Large White Oak Fx thence N° 7° Et 365 poles to Long Marsh 420 poles to 2 Red Oaks and W: Oak in a Poyson'd field by a Road thence N° 65° Wt 134 poles to a W: Oak by ye sd Marsh thence crossing ye Marsh S° 20° Wt 126 poles to another Branch: of Long Marsh 218 po: to a Red Oak Fx thence N° 80° Wt 558 p0: to a Large Red Oak & White Oak Fx in a Valley thence S° 25° Wt 144 poles to a Black Walnut in a Poyson'd Field by a Lime Stone Rock thence S° 33½° Et 96 to a White Oak thence S° 80° Et 316 po. to three Red Oaks in a Bottom in Wm Johnstones line thence with Johnstones S° 80° Et 30 po to a Double Hickory Collo. Blackburns corner 114 po to 3 Hickorys Johnstones corner & corner to ye aforesaid 623 Acre Tract thence along ye lines thereof East 280 poles to 3 Red Oaks finally along another of the lines thereof S° 15° Et 262 po to ye beginning

HENRY ASHBY	
RICHARD TAYLOR	*Chain Men*
ROBERT ASHBY	*Marker*
WM LINDSEY	*Pilot*

The "marker" was probably rodman; the "pilot," instrumentman.

The following notes describe a rectangular lot. Apparently George Washington did not have any difficulties about his closures. Note that the pilot's name is not mentioned. George himself was probably instrumentman.

March 29th 1748. Surveyed for Mr. James Rutlidge ye following a piece of Land Beginning at 3 W. O. in ye Mannor Line by a Path leading to y. Clay Lick & Extending thence N° 44° Wt 164 po. to a White Oak by a Drain at ye foot of a Mountain thence N° 46 Et 487 po. to 2 White Oaks near a Branch call'd Clay Lick Run thence S° 44°Et 164 po. to 2 W. O: & a Hickory in ye Mannor Line Finally along ye Mannor Line Reversed S° 46° Wt 487 po to y. Beginning.

HENRY ASHBY	
RICHARD TAYLOR	*Chain Men*
WM DUNCAN	*Marker*

Washington acquitted himself creditably on the expedition and returned home on Wednesday, April 13, 1748. From the general language of the Journal kept on the expedition, it is clear that he was the Chief of Party — quite a responsibility for a lad of sixteen. It must be remembered that he not only had to survey the tracts, but *find them also*, the general location having been given, but in all probability without a map to guide him.

Having acquitted himself as a man, the young surveyor naturally looked about for permanent employment in his beloved profession. Through the efforts of Lord Fairfax the young man was appointed county surveyor. Being thus licensed, his surveys became clothed with the authority of court records, and — a less desirable state of affairs — he

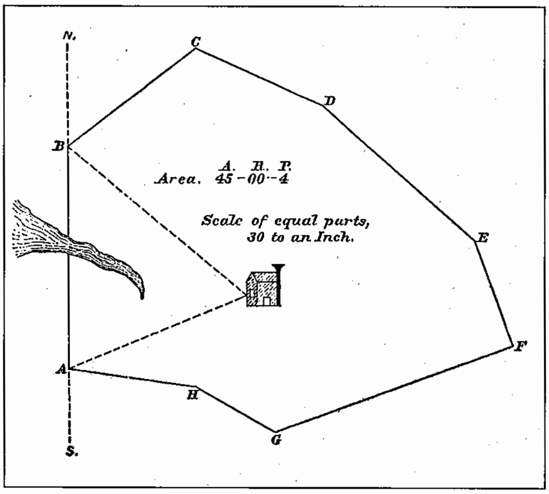


FIGURE 9. Francis Jett's land.

had to pay over part of his fees to William and Mary College, the licensing authority.

For three years in all he practiced his profession. A letter, written by him during this period, describes to some extent his life at the time. The spelling and punctuation are as corrected by Professor Sparks:

> DEAR RICHARD: — The receipt of your kind favor of the 2d instant afforded me unspeakable pleasure; as it convinces me that I am still in the memory of so worthy a friend, — a friendship I shall ever be proud of increasing. Yours gave me the more pleasure, as I received it among barbarians and an uncouth set of people. Since you received my letter of October last, I have not slept above three or four nights in a bed, but, after walking a good deal all day, I have lain down before the fire upon a lit-

TABLE 1.
Survey Data for Francis Jett's Land

Then Survey'd for M^r^ Francis Jett the following Tract of Land Bounded as p^r^ Field Book.

[Station]	[Course]	[Poles]
A	N	56.15
B	N 51–00 E	39.19
C	S 65–00 E	34.14
D	S 49–00 E	50.15
E	S 70–00 E	29.00
F	S 70–00 W	62.13
G	N 58–30 W	20.24
H	S 83–30 W	30.00

Remarks y^e^ distance from A to B being Inaccessable I took an angle within y^e^ field from A to a house bearing N 73°–00 E 46 Pole thence to B bearing N 48–00 W.

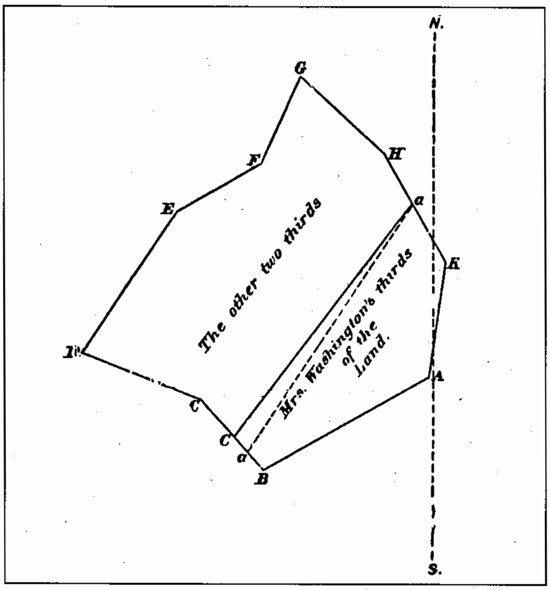


FIGURE 10. Elizabeth Washington's land.

TABLE 2.
Survey Data for
Elizabeth Washington's Land

Survey'd for M^rs^ Elizabeth Washington y^e^ Following Tract of Land whose thirds is required to be laid of 20 Pole from H towards K & the Division line to run towards BC.

A	S 54,, 00 E	67,, 00
B	N 45,, 00 W	36,, 00
C	N 76,, 00 W	45,,—
D	N 31,, 00 E	60,,—
E	N 56,, 00 E	35,,—
F	N 21,, 00 E	30,, 24
G	S 51,, 00 E	40,, 20
H	S 34,, 00 E	41,, 60
I	S 04,, 00 W	34,, 20

Area	Acres	Roods	Perch
	52,,	1,,	39,,

tle hay, straw, fodder, or a bearskin, whichever was to be had, with man, wife, and children, like dogs and cats; and happy is he, who gets the berth nearest the fire. Nothing would make it pass off tolerably but a good reward. A doubloon [about $7, 1932 dollars] is my constant gain every day, that the weather will permit of my going out, and sometimes six pistoles [three doubloons]. The coldness of the weather will not allow of my making a long stay, as the lodging is rather too cold for the time of the year. I have never had my clothes off, but have lain and slept in them, except the few nights I have been in Frederictown.

His notes were neatly kept as usual. The following examples will no doubt be of interest. The first example is a survey of Mr. Francis Jett's land (see Figure 9 and Table 1). Note how he measured his line across the stream. Figure 10 and Table 2 illustrate another survey. Figure 11 is the plat of a lot, and is also used as the title-page for a field book:

Survey'd for Richard Barnes Gent^{n} of Richmond County a certain Tract of Waste and ungranted Land Situate Lying and being in the county of Culpeper and Bounded as followeth Beginning at three white Oaks in Normans Line and Corner Trees to (Aaron Pinson's now) M^{r} Barnes's Land & Extending thence N° 42° 30′ W^{t} Ninety five Poles to a Branch of Flat Run Two hund^{d} and Eighteen Poles to a Large White Oak Corner to Norman thence along another of his Lines N° 39° E^{t} Thirty four Poles to three white Oaks & a Hickory Cor: to the said Norman and John Roberts thence along Robert's Line S° 78° W^{t} One hund^{d} and Eighty three Poles to the Road that Leads over Norman's Foard Two hund^{d} and Sixteen Poles to two white Oaks in a Glade Cor^{r} to the said Roberts and M^{r} Francis Slaughter thence with the said Slaughters Line S° 5° W^{t} One hund^{d} and Sixty four Poles to three white Oaks in the said Slaughter line thence leaving his Line S° 66° E^{t} Two hund^{d} and thirty Six Poles to three white Oaks amongst a Parcel of Rock Stones Barnes's Corner thence with his Line N° 53° E^{t} One hund^{d} and Eighty Six Poles to the Beginning Containing Four Hundred Acres this Twenty Second Day of July 1749.

WASHINGTON SCC

JOHN LONEM
EDWARD CARDER *Chain Men*
EDWARD HOGAN *Marker*

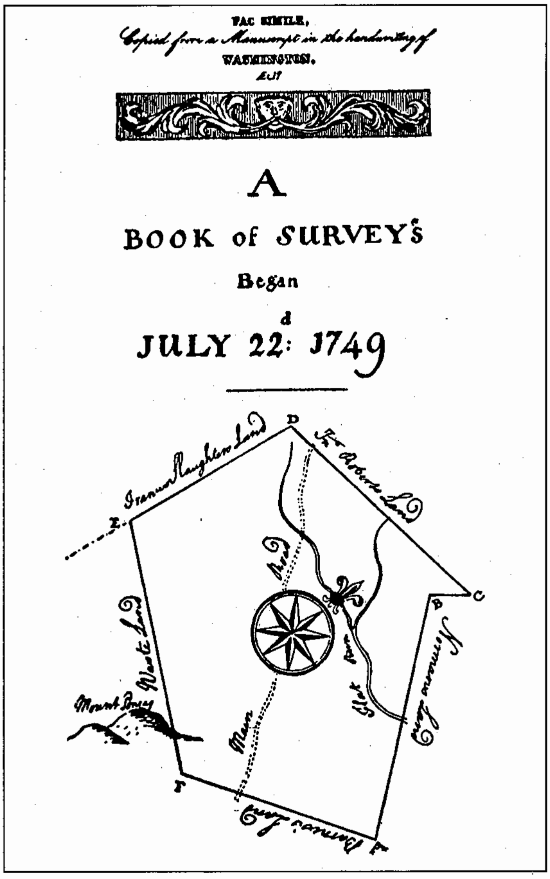


FIGURE 11. Survey for Richard Barnes.

"Washington SCC" is supposed to mean "Washington, Surveyor Culpeper County."

Figure 12 represents two lots of a subdivision on the "Cacapehon" or Lost River (so-called because for three miles it is subterranean). They belong to Francis and William McBride. A similar lot belonging to a Robert Denton adjoins it. Figure 13 represents an additional survey on the Lost River.

George Washington did quite a bit of surveying in that region. He was, in fact, a very

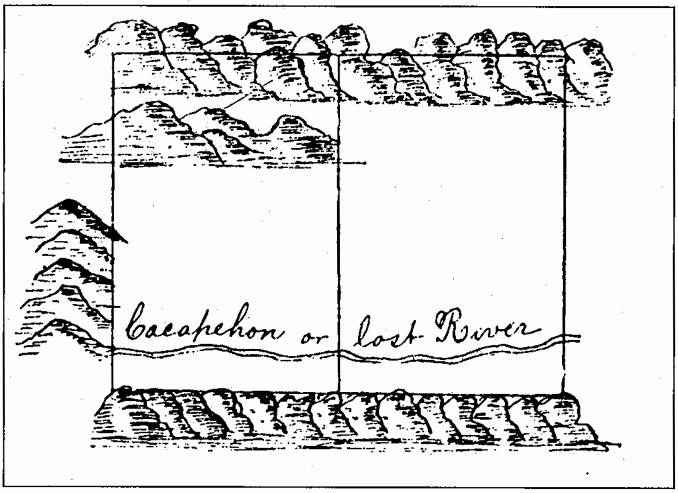


FIGURE 12. The lands of Francis and Williams McBride, Lost River.

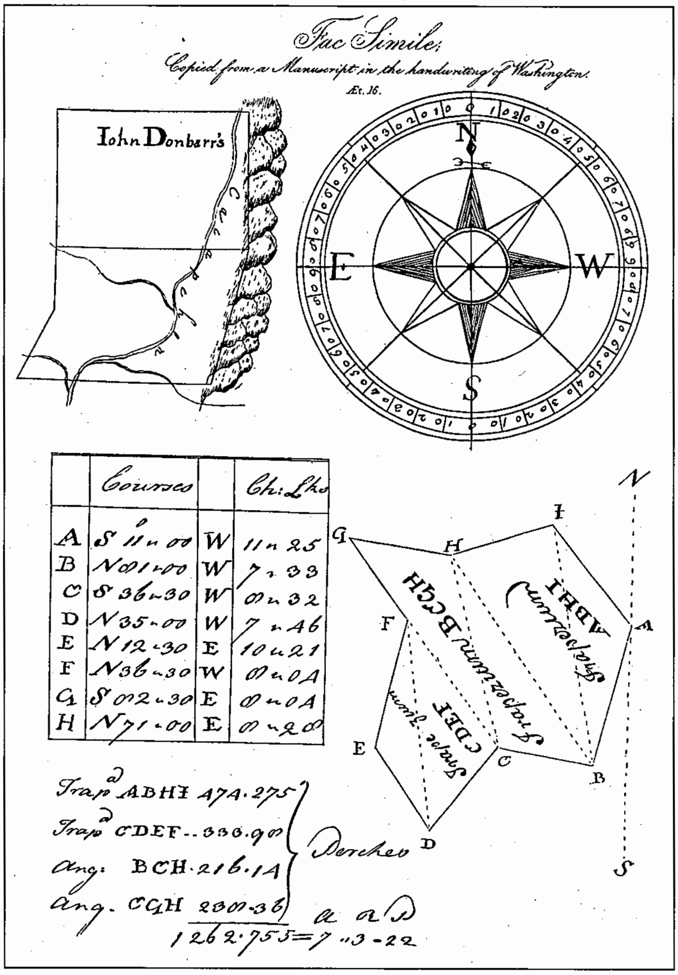


FIGURE 13. Another survey on the Lost River.

popular surveyor, his popularity being due to his exactitude. Later surveys — and even recent ones — could not find any errors in his courses and measurements.

This is all the more remarkable when we remember the numerous sources of error possible with a chain, and that a great deal of surveying in Washington's time was done by means of the chain alone, the angles being laid out by latitude and departure measurements in the field, with the values found in tables of natural functions of angles. If we recollect rightly, "Breed and Hosmer" does not include this method as standard.

But this phase of his career was soon to close. His elder brother Lawrence became ill of pulmonary tuberculosis and went to Barbados to cure himself. George went with him. The tropical air was of no aid to the sufferer, however. Lawrence Washington died. George came back to live at Mount Vernon, the property having become his.

He soon left home to fight in the French and Indian War, having been appointed a major in the provincial forces. He came back, covered with glory and the foremost soldier in the colonies.

At Mount Vernon he stayed from the close of the French and Indian War to the outbreak of the Revolution. During that time he married, became a vestryman, a Burgess, and quite a power in the community. Of his services in the Revolution we need not speak here.

Washington, the Farmer

We will now pay some attention to our first President as an agriculturist. In these days, when there are enough varieties of engineers to make Vitruvius turn over in his grave, it is rather difficult to forbear enrolling our illustrious subject in the ranks of agricultural engineers.

He designed all his farm buildings, experimented with crops and ran an experiment station of his own, the results of which he put to good use in running his estate. Of his plans for agricultural buildings, Figure 14 shows part of his plan for a sixteen-sided barn, built in 1793. He calculated that 140,000 bricks would be required for it. These were made on the estate. The threshing-floor was 30 feet square with 1½ -inch spaces left between the boards so that the grain when trodden out by horses or beaten out with flails would fall through to the floor below, leaving the straw above.

He constantly endeavored to rouse his neighbors from their shiftlessness, but to no purpose. They persisted in their unscientific farming and envied his profits. Lack of space does not permit examples of his minute planning for rotation of crops.

Not only was he the country's foremost agriculturist, but he devised and used much labor-saving machinery. The following extracts from a letter to Theodoric Bland describe and explain the use of a "drill plough" which he devised:

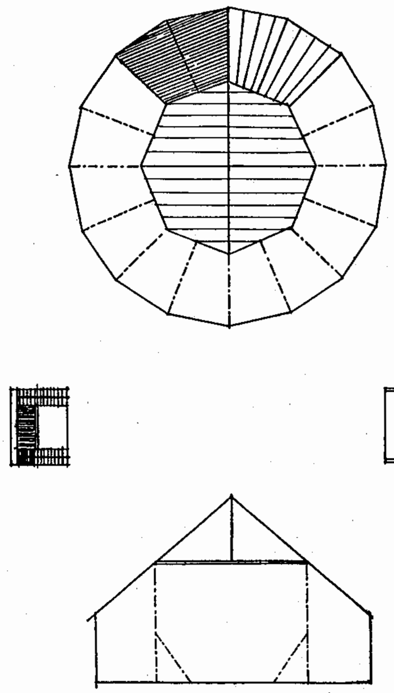


FIGURE 14. Washington's sixteen-sided barn (from his plan).

MOUNT VERNON,
28 December 1786.

DEAR SIR: — I am now about to fulfill my promise with respect to the drill plough and timothy seed. . . .

To give you a just idea of the use and management of it, I must observe that the barrel at present has only one set of holes, and those adapted for the planting of Indian corn, only eight inches apart in the row; but by corking these, the same barrel may receive others of a size fitted for any other grain. To make the holes, observe this rule; begin small and increase the size, till they admit the number of grains, or thereabouts, you would choose to deposit in a place. They should be burnt, and done by a guage, that all may be of a size, and made widest on the outside to prevent the seeds choking them. You may, in a degree, emit more or less through the same holes, by increasing or lessening the quantity of seed in the barrel. The less there is the faster it issues. The compressure is increased by the quantity, and the discharge is retarded thereby. The use of the band is to prevent the seeds issuing out of more holes than one at a time. It may be slackened or braced according to the influence the atmosphere has on the leather. The tighter it is, provided the wheel revolves easily, the better. By decreasing or multiplying the holes in the barrel, you may plant at any distance you please. The circumference of the wheels being six feet, or seventy-two inches, divide the latter by the number of inches you intend your plants shall be asunder, and it gives the number of holes required in the barrel.

By the sparse situation of the teeth in the harrow, it is designed that the ground may be raked without the harrow being clogged, if the ground should be cloddy or grassy. The string, when this happens to be the case, will raise and clear it with great ease, and is of service in turning at the ends of rows; at which time the wheels, by means of the handles, are raised off the ground, as well as the harrow, to prevent the waste of seed. A small bag, containing about a peck of the seed you are sowing, is hung to the nails on the right handle, with a small tin cup the barrel is replenished with convenience, whenever it is necessary, without loss of time, or waiting to come up with the seed-bag at the end of the row. I had almost forgot to tell you that, if the hole in the leather band, through which the seed is to pass, when it comes in contact with the hole in the barrel, should incline to gape, or the lips of it turn out, so as to admit the seed between the band and the barrel, it must be remedied by riveting a piece of sheet tin, copper, or brass, the width of the band, and about four inches long, with a hole through it, the size of the one in the leather. I found this effectual. I am, dear Sir, &c.

He must have sent a sketch with the letter. The spelling and punctuation are as corrected by Professor Sparks.

Washington kept a diary, from which are taken the following extracts:

> January 1st 1760 — Visited my plantations, and received an instance of Mr. F.'s great love of money, in disappointing me of some pork because the price had risen to twenty-two shillings and sixpence after he had engaged to let me have it at twenty. Found Mrs. Washington upon my arrival broke out with the measles.
>
> 8th Directed an indictment to be formed by Mr. Johnston against J. B. for a fraud in some iron he sold me.

Evidently Colonel Washington believed in living up to specifications:

> February 10th Ordered all the men from the different quarters to assemble at Williamson's quarter in the morning to move Petit's house.
>
> March 6th Fitted a two-eyed plough, instead of a duck-bill plough, and with much difficulty made my chariot wheel-horses plough.
>
> 7th — Put the pole-end horses into the plough in the morning and put in the postillion and hind horse in the afternoon, but the ground being well swarded over, and very heavy ploughing, I repented putting them in at all, for fear it should give them a habit of stopping in the chariot.
>
> 14th — Mr. Carlyle and his wife still remained here. We talked a good deal of a scheme of setting an iron-works on Colonel Fairfax's land on Shenandoah.
>
> 17th — Went to my mill and took a view of the ruins, which the fresh had caused; determined, however, to repair it with all expedition, and accordingly set my carpenters to making wheel and hand barrows.
>
> 19th — Peter (my smith) and I, after several efforts to make a plough after a new model, partly of my own contriving, were fain to give it over, at least for the present.
>
> 26th — Spent the greatest part of the day in making a new plough of my own invention.

When he had no machinery, he just went ahead and made it himself.

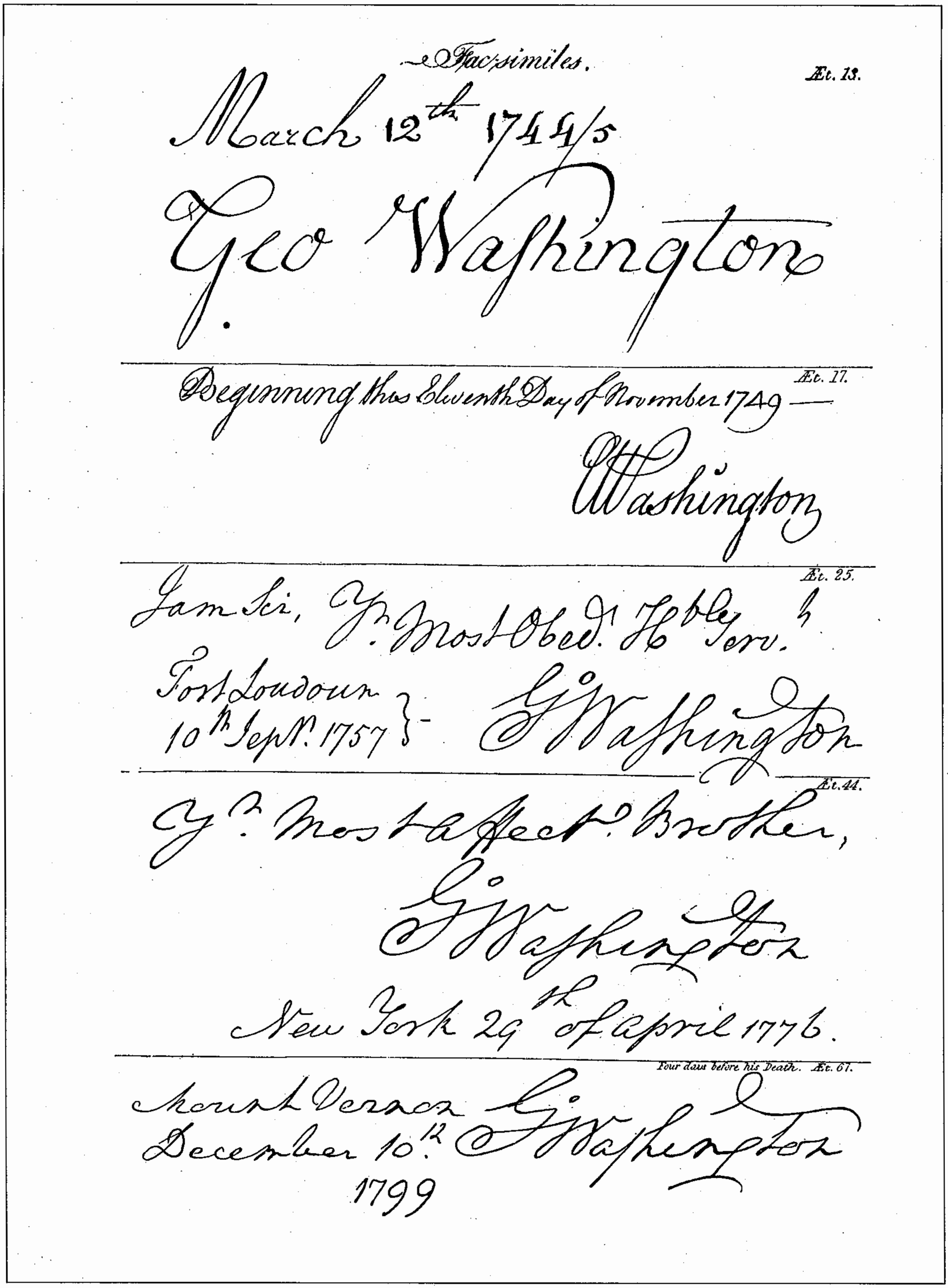
Washington, Land Developer

As a land developer he was way ahead of his time. He knew that the young, lusty Nation must grow. In order to grow, it must have more land. He therefore lent all possible aid to settlers in the West. He bought up a lot of land in the Ohio country, which he tried to rent out to cultivators. A great deal of the land he received for services in the French and Indian War; some he bought; some he staked out from unappropriated lands offered by Virginia.

He organized or took part in several companies whose aims were to develop waste land, such as the Great Dismal Swamp company, the Mississippi Company and others.

Other Interests

Another great interest of his was in opening the navigable streams, so that the western part of the country might be connected by a network of canals with the eastern part. He held that when communications are easy the country can grow and be united.



Facsimiles of Washington's handwriting at 13, 17, 25, 44 and 67 years of age (from top to bottom). The last sample was from four days before his death.

In a letter to Richard Henry Lee, President of Congress, he urged that the western waters be explored, their navigable capabilities ascertained, and a complete map be made of the country; that in all grants for land by the United States there should be a reserve made for special sale of all mines, mineral and salt springs, and that a medium price should be adopted for the western lands, sufficient to prevent monopoly, but not to discourage useful settlers.

It is surprising how modern he was in all his views. The program mapped out to Mr. Lee is in many ways paralleled by recommendations made in recent directors' reports of the various government bureaus in charge of these matters. So far, of course, no systematic schemes have been followed. The country, for example, is not even now completely mapped in accordance with United States Geological Survey Standards. Neither has the Coast and Geodetic Survey been able to set itself a program that would be supported by Congress financially.

That Washington had good judgment on the use of various building materials, with which he was experimenting constantly, may be gathered from the following extract from a letter to Count de Moustier, under date of December 15, 1788:

> I have formerly been somewhat curious in making experiments relative to cements; particularly that which derives its name from Loriot, but have never been able to succeed to my wishes. I was delighted with the idea that the cement used by the ancients had in all probability been rediscovered. Some time in the late war I employed three or four-of the principal French engineers in our army to make some mortar into a consolidated mass [concrete?], according to the printed directions for making Loriot's cement, with a copy of which they were furnished. But the result, after many trials, was infinitely distant from what we have been led to expect. As the process was strictly in conformity to the prescribed rules, I know not to what cause the failure of success should he attributed.

That he knew what good bricks are may be seen from the following instructions to his brickmakers, making bricks for a barn:

> Gunner and Davis must repair to Dogue Run and make bricks there, at the place and in the manner which have been directed, that I may have no salmon bricks in that building.

Several books have been written concerning his supervision of the planning of Washington City by Major l'Enfant, so that no mention need be made here.

During the canalization of the Potomac River, one of the engineers proposed a means of doing away with the locks at the rapids. President Washington's opinion, expressed in a letter to Tobias Lear (December 21, 1794), is most interesting:

> The plan of Mr. Clairborne's engineer, as far as I understand it, is to avoid locks altogether. The vessels are received into a basket, or cradle, and let down by means of a lever and pulleys, and raised again by weight at the hinder extremity of the lever, which works on an axis at the top of a substantial post fixed about the center of the lever. On this principle, but differently constructed, Mr. Greenleaf a few months ago showed me a model of the efficacy of which he seemed to entertain the most exalted opinion. My doubts of the utility of both arise first, from the insufficiency of any machinery of this sort to bear the weight of the cradle when charged with water and a loaded boat therein, and its aptness to get out of order by means thereof; secondly, I do not find that they are in general use; and thirdly, because if I recollect rightly, Mr. Weston has told me, but of this I am not certain, that no method of raising and lowering boats has been found equal to that of locks. Still, as I observed in my last, I should be for hearing the opinions and explanations of any and every scientific and practical character that could be easily got at on this subject, and therefore would hear Clairborne's engineer, as well as Mr. Weston. . . .

He gave great encouragement to James Rumsey, who was working on the invention of a steamboat. Rumsey, however, died in London before he could perfect it.

In 1780 the American Philosophical Society elected him to membership. The following letter to President Reed was written in reply to the announcement of his election:

MORRISTOWN,
15 February, 1780

SIR: — I am much indebted to your Excellency for announcing my election as a member of the Philosophical Society. I feel myself particularly honored by this relation to a society, whose successful efforts for promoting useful knowledge have already justly acquired for them the highest reputation in the literary world. I entreat you to present my warmest acknowledgments and to assure them that I shall with zeal embrace every opportunity of seconding their laudable views, and manifesting the exalted sense I have of the institution. The arts and sciences essential to the prosperity of the State, and to the ornament and happiness of human life, have a primary claim to the encouragement of every lover of his country and of mankind. With the greatest respect and esteem, I am, Sir, &c.

Conclusion

Such are the highlights of the unemphasized parts of George Washington's career. Full justice has not been done, owing to lack of space. It is hoped that enough has been said to make us all proud of George Washington, not only for what the world knows him as — a soldier, statesman and patriot — but also as a high type of engineer.

EDWARD GROSSMAN *was an engineer whose offices were located on Tremont Street in downtown Boston. He published a number of articles in the* Journal of the Boston Society of Engineers *and was elected an Associate Member of BSCE in December 1927.*

NOTES — *This article was reprinted, with minor stylistic changes, from Volume XIX, No. 3, of the* Journal of the Boston Society of Civil Engineers *in March 1932. Spellings and usages from Mr. Grossman's original article have been retained, including those from his source material.*

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What Happened to Nantucket?

Making the right choices in designing our built areas is important to their success and longevity.

BRIAN BRENNER

A while back I biked with my son out to Madaket on the western edge of Nantucket Island. It was about a six-mile bike ride from the center of the old whaling village. It was cloudy and cool, the type of dreary day at which Nantucket excels. On the beach looking west over the water, you could see every shade of gray imaginable. The mottled sky blended into the gently swelling water. There wasn't a foghorn blaring in the distance, but you could imagine one. Probably out on the horizon floated a lost, seventeenth-century ghost ship.

The beaches of Nantucket are among the most beautiful in New England, which is a large part of the island's appeal. There is nothing particularly unique about a beach in summer, but on Nantucket it's not only summer: it's moody. At Madaket, the blueish gray swells gently lapped the sand, edging against the shells and driftwood. Along with the imaginary foghorn and the real sea gulls, it was a great place for reflection — in this case, I gave pause to reflect about infrastructure.

In With the Old

In addition to the beach and ocean, Nantucket has an amazing old fishing village. The village — a collection of preserved old buildings and cobblestone streets — is perched on a gentle hill sloping down to its well-protected harbor. In the nineteenth century, Nantucket was the whaling capital of the world. Many blocks feature the large, graceful homes of the former whaling ship captains. For a brief period of time before the discovery and use of petroleum, Nantucket supplied much of the world's whale oil. This substance was used to light the lamps all over the world, so the island was very wealthy. The whaling captains built spacious, grand mansions with widow walks and fancy turrets.

What is impressive about the village is not just that it's old and preserved, but that the buildings and streets are well-designed and appealing. It's not only the individual structures, but the way they come together to form public space as a whole. The structures are situated to create pleasant outdoor spaces. Each street is a human-scaled outdoor room with trees and private structures spaced at just the right proportions to create inviting open public areas. Walking around this village, whether on the bustling main street or in the back alleys and side streets, is enjoyable and exciting. There, in Nantucket village, the sum ends up being greater than the constituent parts.

However, times change and Nantucket is no longer wealthy from catching whales but now prospers because of tourism. A lot of money has gone into restoring and maintaining the old village. Probably the village spaces would be a lot less appealing if they were run down and not maintained. That intimate public street space would feel oppressive and threatening if the surroundings were physically decaying. Also, the island is a vacation destination, populated by hundreds of carefree, happy people. Being surrounded by these people goes a long way towards making a public place enjoyable.

The Best Infrastructure Design

Yet, even with these considerations, it's important to consider how the infrastructure design and layout creates such a worthwhile place. Compare downtown Nantucket village to your local strip mall. The layout of stores, roads and infrastructure in the strip mall creates spaces where the sum is more often than not less than the constituent parts. The implied message by the design of the mall parking lot is that you need to get out of it and into the store as quickly as possible. In fact, this is exactly what is intended and expected.

It's not really a question of old and new, either, but of infrastructure design. The old seems quaint and desirable. The new seems pathetic. However, it's not because one is old and the other is new, but because of the scale of the man-made environment and what the structures and facilities make out of the individual parts. New infrastructure can be well-built and designed. Old infrastructure can be poorly built and designed, although we tend not to see it because badly designed old infrastructure ends up demolished and replaced.

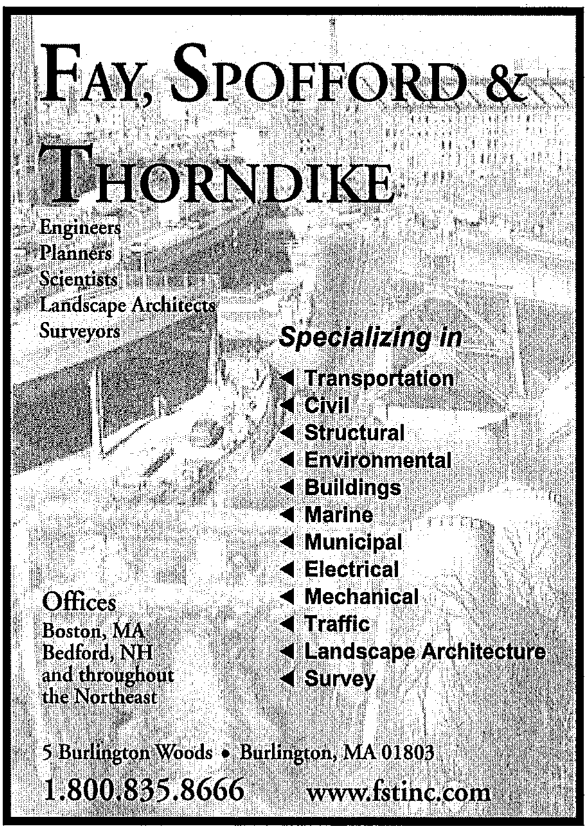
The forces responsible for your local strip mall and office parks are also at work on Nantucket. The island is not immune to them. Between the mournful gray seashore and the village are stretches of moors and scrub pine woods. In the past, there was a distinct edge between the village and the countryside. That edge has now been blunted, suburban Nantucket style. Large summer homes have been plopped down on plots of land. The homes, while individually beautiful and attractive, tend to have no spatial relationship to each other. In fact, they seem to have been dropped from the sky onto the landscape. Instead of creating a beautiful village like the old whaling captains' mansions, these new mansions create a peculiar "plopscape" of private spaces on what used to be the moors and woods of the hinterlands. You can see this effect most distinctly by biking down the old Polpis Road on the island's northeast side. The hulking summer homes seem to be a chic, gray-shingled parody of housing, and, taken as a whole, the landscape is far from inviting.

How to Handle Development

The residents of Nantucket have been involved in an intense debate about development. Even though it's an island, there are an awful lot of cars in the summer. The vehicles all congregate in congested, fume-laden traffic jams. While the village is dense and walkable, and you can bike to the beaches, it's really necessary to have a car (or two or three) to access the distant summer homes plopped all over the island. To address the problem, the town has introduced a mass transit system of sorts. There are now several bus routes. Yet, the key issue — that of land use and private rights versus public impacts — remains to be addressed in any meaningful way. In that sense, Nantucket is a microcosm of the land use trends and issues faced all over the United States.

You can still experience and imagine Nantucket as it was. To the island's credit, much of the moors and woods have been preserved, particularly along the Milestone Road in the island center. But the twenty-first-century version of Nantucket seems to have been degraded from its past beauty. The beaches and village are still wonderful, but you need to hold your nose at much of what has recently been built in between.

BRIAN BRENNER *is Senior Professional Associate with Parsons Brinckerhoff, working with Bechtel/Parsons Brinckerhoff on the Central Artery/Tunnel Project. He served as Chair of the editorial board for* Civil Engineering Practice *for seven years.*



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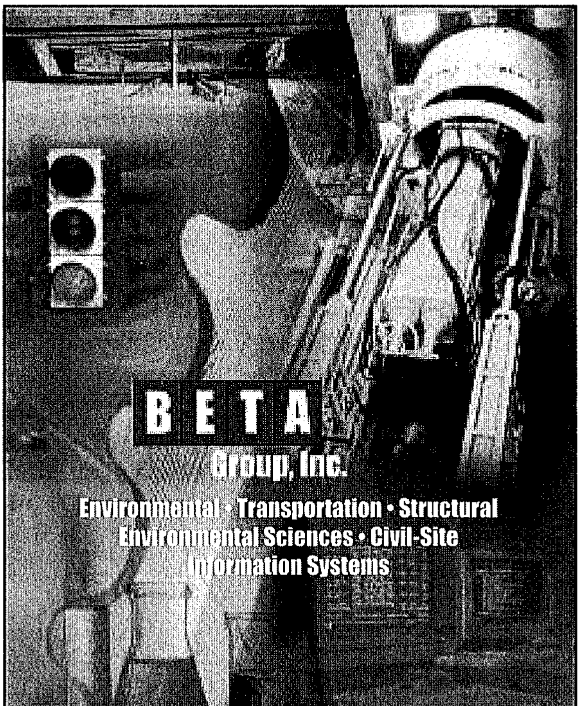

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