Anatomy of a Court Trial on Tank Settlements

Adequate preparation and an in-depth understanding of the role of the expert witness in legal proceedings are key to presenting an effective case in court.

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In 1969, PPG Industries, Inc. (formerly known as Pittsburgh Plate Glass, PPG), decided to establish a marine terminal on the east coast of the United States for the importation of chemicals from a production facility in Puerto Rico. The selected site lies in New Jersey near the Delaware River and is underlain by a soil profile that includes thick layers of a soft organic silt. The terminal consisted of several flexible bottom steel storage tanks, which were constructed from 1970 to 1971. The tanks settled more than predicted by the geotechnical consultant, Dames & Moore (D&M), and the two largest tanks were subsequently placed on pile foundations in 1975. PPG brought suit against D&M to retrieve the costs associated with the settlement and piling of the tanks.

Project Initiation

PPG acquired an option to purchase a 132-acre site on land at the confluence of Mantua Creek and the Delaware River near the town of Paulsboro, New Jersey. Initial development of the Mantua Terminal was handled by the Central Engineering Department of PPG's Chemical Division, but with the objective of finding an independent terminal operator which would take over its construction and then operate the terminal for other users in addition to PPG. PPG also hired an engineering-contractor (EC) to assist with the design and construction of the facility. *Neither PPG nor the EC had any geotechnical expertise.*

Five companies were requested in May 1969 to submit priced proposals for the foundation design of the storage tanks. Of these, the only two geotechnical firms (one being D&M) both declined to bid for the work, explaining that bidding was not appropriate since the scope of required work was too ill defined. In any case, PPG hired a drilling company, Sprague & Henwood (S&H), which subcontracted the soil testing and evaluation to a materials testing laboratory (MTL) which, in

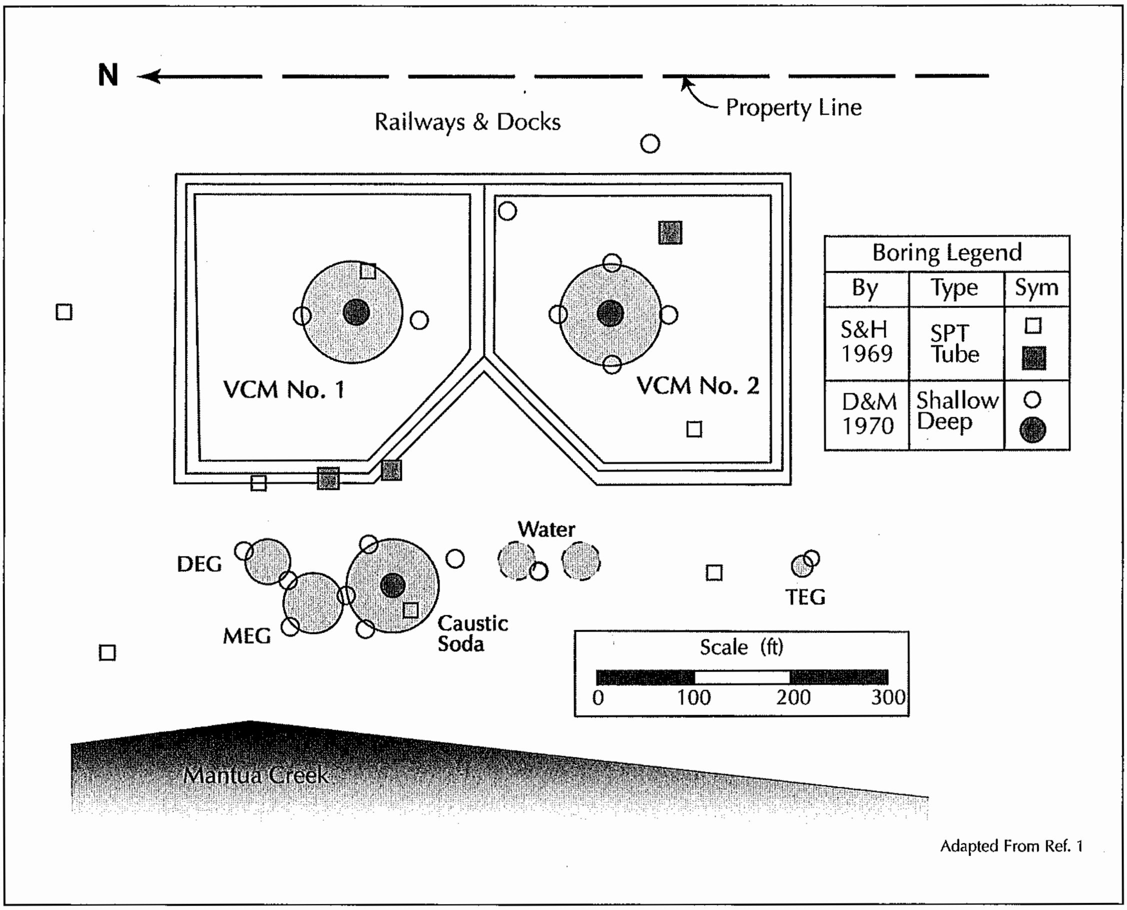

FIGURE 1. Location of storage tanks and borings at Mantua Terminal.

turn, hired an academic as its geotechnical consultant.

S&H drilled three shallow and eight deep borings, *at locations specified by PPG*, and sent three tubes to the MTL, which performed three one-dimensional consolidation (oedometer) tests, apparently without any Atterberg limits or measurements of undrained shear strength. The report by the MTL indicated that the foundation soil profile consisted of a surface layer of organic material and loose sand (which would have to be partially removed and replaced with 10 feet of structural fill prior to tank construction) underlain by two thick layers of "organic river silt" founded on dense sand and gravel. With replacement of the surface material, the report indicated an allowable bearing pressure of q_a equal to 4,000 pounds per square foot (psf) and that under this loading, tank settlements of 0.8 and 3.1 inches would occur in about six months beneath the edge and center, respectively, of a 112-foot-diameter steel tank.

Meanwhile, the EC was proceeding with the design phase of the work, based on the recommendations in the MTL's report, and PPG purchased the site in December 1969 with a project budget of $7.5 million. Figure 1 shows a plan of the Mantua Terminal with the location of the chemical storage tanks and the S&H borings. The size and contents of these flexible bottom, steel tanks were as follows.

- *Vinyl chlorine monomer* (VCM): two tanks of 105 feet in diameter with a product height of 65 feet. VCM is an extremely hazardous material that needs to be stored under refrigerated conditions as a

TABLE 1.
Timeline of Principal Events During the Design, Construction & Water Testing of Storage Tanks

Time		Owner Actions	D&M Participation
1969	May	RFP for Foundation Design	
	July to Aug.	Initial Site Investigation & Tank Foundation Design	
	Sep. to Oct.	EC Starts Final Design	
1970	Early Apr.	Construction Stopped	Hired for Shallow Borings
	Mid-Apr.		Deep Borings & Lab Testing
	Mid-May		Report With Redesign & Instrumentation
	Early June		Proposal for Instrumentation & Water Testing Monitoring
	Early July	Proposal Rejected	
	Nov. to Dec.	First Water Testing (DEG, MEG, Caustic)	(Weekly Data *Not Sent* to D&M)
1971	Mid-Jan.	Water Testing Data Sent to D&M	Revised Settlement Analyses With Lower Prestress
	Mar. to Apr.	Second Water Testing (DEG, MEG, Caustic) First Water Testing (VCM 1 & 2)	Revised Analyses With Even Lower Prestress, Computer Program to Fit VCM Settlement-Time Data
	May to July	Second Water Testing (VCM 1 & 2) D&M Terminated	Good Agreement Between Predicted & Measured Behavior
Dec. 1971 to Jan. 1972		Tanks Put in Service	
Feb. 1972		Letter Criticizing D&M's Work	No Reply

liquid (the unit weight is 3 percent less than water). At natural temperatures, it is an extremely inflammable and potentially explosive gas.

- *Caustic soda:* one tank 94 feet in diameter with a product height of 42 feet and a unit weight of 96 pounds per cubic foot (pcf).
- *Mono-, di- and tri-ethylene glycols* (MEG, DEG and TEG): three tanks with diameters ranging from 20 to 57 feet.
- *Water:* two tanks 35 feet in diameter.

Table 1 summarizes the principal events related to the design, construction and water testing of the storage tanks from 1969 through 1972.

Initial Construction & Redesign

In mid-March 1970, PPG had found a terminal owner-operator (TO) that took over the project with an anticipated one-year construction period. It was also agreed by this time that the 10 feet of structural fill recommended in the MTL report would be largely replaced by using vibroflotation to densify the upper loose sands in order to save costs. But shortly after starting this foundation improvement program, there was concern about the large quantity of unsuitable material that had to be replaced prior to commencing work with vibroflotation. Consequently, construction was stopped and D&M was hired in mid-April to make some twenty shallow borings to a depth of 20 feet in order to resolve this problem.

After reviewing the S&H boring logs, D&M on its own initiative made one deep boring and concluded that the tank settlements would be much larger than indicated in MTL's report. D&M then got permission to expand its scope of work to include three deep borings (see Figure 1 for the location of the shallow and deep borings), twenty-nine D&M tube samples with thirty-one Torvane and miniature lab vane measurements of undrained shear strength and five oedometer tests with Atterberg limits. D&M also performed settlement and stability analyses in order to develop revised foundation designs for the various tanks.

The above geotechnical studies led to five reports and meetings over a period of two weeks (remember that time was critical since construction had been halted).

The first D&M verbal report to the EC on May 1 indicated that:

- The top 8 to 10 feet of material should be replaced.
- The prior allowable stress of q_a equal to 4,000 psf would lead to settlements of 2 to 3 feet (rather than only 3 inches) and may have to be reduced to only 2,000 to 2500 psf.
- The VCM tanks could have a differential settlement (δ) tolerance between the tank center (ρ_C) and edge (ρ_E) of 21 inches.
- Alternate designs could include staged filling, larger diameter tanks, more tanks and piling.

The second report from D&M, a progress report to the EC for the VCM tanks on May 8, concluded that:

- q_a would be approximately 3,000 psf, leading to a tank diameter of 121 feet for same volume.
- For this tank loading and diameter, the estimated final consolidation settlements for the north and south tanks would be ρ_C equal to 16 and 19 inches at the center and ρ_E equal to 3 and 4 inches at the edge. These estimates were calculated for a preload stress (preconsolidation stress, σ'_p, minus the initial effective overburden stress, σ'_{v0}) within the organic silt layers of 1,200 psf. The resulting differential settlement of 13 to 15 inches was less than the allowable δ of 21 inches.
- It would be prudent to use an undrained factor of safety (FS) of 1.5 to 1.6, versus the usual FS of approximately 1.2 to 1.3 for steel storage tanks, due to the hazardous nature of VCM and construction at a new site.
- *Loading above about 3,000 psf could cause excessive unpredictable settlements due to plastic flow of the organic silt layers.* (Note: Plastic flow refers to undrained shear deformations within a zone of the foundation soils wherein the shear stress in the soil equals the undrained shear strength of the soil. Such shear deformations cause lateral spreading [squeezing] of the soil and, hence, increased tank settlements.)

The third report was presented by D&M at a meeting with the EC, PPG and the TO on May 11:

- D&M presented the above estimated settlements for two 121-foot-diameter VCM tanks loaded to q_a equal to 3,000 psf, and also noted "a real need for checking settlement" during water testing. (Note: Flexible bottom steel storage tanks are filled with water [water tested] to check their integrity before being put in service. Water testing also may be used to preload the foundation soil in order to reduce in-service tank settlements. Such preloading is often accompanied by mud jacking to restore the initial crown of the tank bottom.)
- Increasing the tank diameter would cause a five- to six-week delay (needed to order the new steel), while piling would add

$400,000 to $500,000 to the foundation costs.

The fourth report given by D&M at a meeting with the the EC, PPG, the TO and the MTL and its consultant on May 12 was held apparently to resolve the differences between the D&M and the MTL recommendations for the VCM tanks. (MTL's consultant also stated that MTL had recommended a q_a of 3,600 psf and someone else had increased it to q_a of 4,000 psf.) This meeting resulted in:

- A compromise loading of q_a equal to 3,300 psf being agreed to. The original VCM tank diameter of 105 feet would be retained, but the uppermost row of steel plates was eliminated to lower the tank height from 65 to 55 feet.
- D&M's proposed monitoring program during water testing of the VCM tanks being agreed to. This program included a prolonged loading period with steam heating to prevent freezing during the winter, installation of piezometers to record pore water pressures within the organic silt layers and the use of Varec gages to provide direct measurements of the settlement of the tank bottom.

The last report D&M presented on May 15 to the EC, "Foundation Investigation of Proposed VCM and Caustic Tanks," indicated that:

- For the VCM tanks, D&M recommended q_a equal to 3,300 psf and quoted the same predicted settlements as cited in the May 8 progress report, along with predicted times to reach 90 percent consolidation of one to two years.
- For the caustic tank, D&M recommended initial water testing to q equal to 2,600 psf, then to q equal to 3,300 psf with caustic soda for 45 days before final loading to q_a equal to 4,000 psf — *i.e.*, the use of staged loading to preload the foundation soils.
- *The accuracy of the computed settlement magnitudes was considered to be ±25 percent*, which when applied to the computed δ of 15 inches for the south VCM tank, gives a maximum differential settlement of 19 inches (compared to the tank tolerance of 21 inches).
- The two VCM tanks would be filled to q_a equal to 3,300 psf over twenty days and then maintained for a period to one to two months. These tanks and the caustic tank would have piezometers to record pore pressures and Varec gages to obtain accurate measurement of bottom settlements.

The report *did not discuss the possibility of excessive settlements due to plastic flow at* q *equal to 3,300 psf*, even though the computed settlements included only those due to one-dimensional consolidation.

Figure 2 summarizes the essence of D&M's May 15 report regarding the VCM tanks. The typical soil profile has two organic layers of 20 to 25 feet in thickness separated by a thin sand stratum overlying dense and gravel. Excluding the one oedometer test on peat, the other four tests had (mean ±1 standard deviation) a natural water content equal to 61 percent (±7.5 percent), a liquid limit equal to 78 percent (±5 percent) and a plasticity index equal to 42 percent (±5 percent). The Atterberg limits straddle the A-line on Casagrande's plasticity chart, leading to an OH-CH classification. The selected prestress of 1,200 psf within the organic soil was based on a combination of the oedometer and undrained strength data. (Note: Although all settlement calculations used the same stress history, the strength tests indicated that the upper organic layer beneath the caustic tank was about 50 percent stronger than under the VCM tanks.)

On May 25, 1970, the EC supplied information to the state of New Jersey for a permit to construct the tank foundations at the Mantua Terminal. The EC stated that D&M would be involved with the water testing program and specific reference was made to the installation of piezometers under the VCM and caustic tanks, along with measurements of settlement both along the outside edges and inside the tank throughout the water testing program. On June 4, D&M submitted a proposal to the EC that detailed the scope and objectives of the water testing monitoring program. D&M would install the piezometers (along with soil

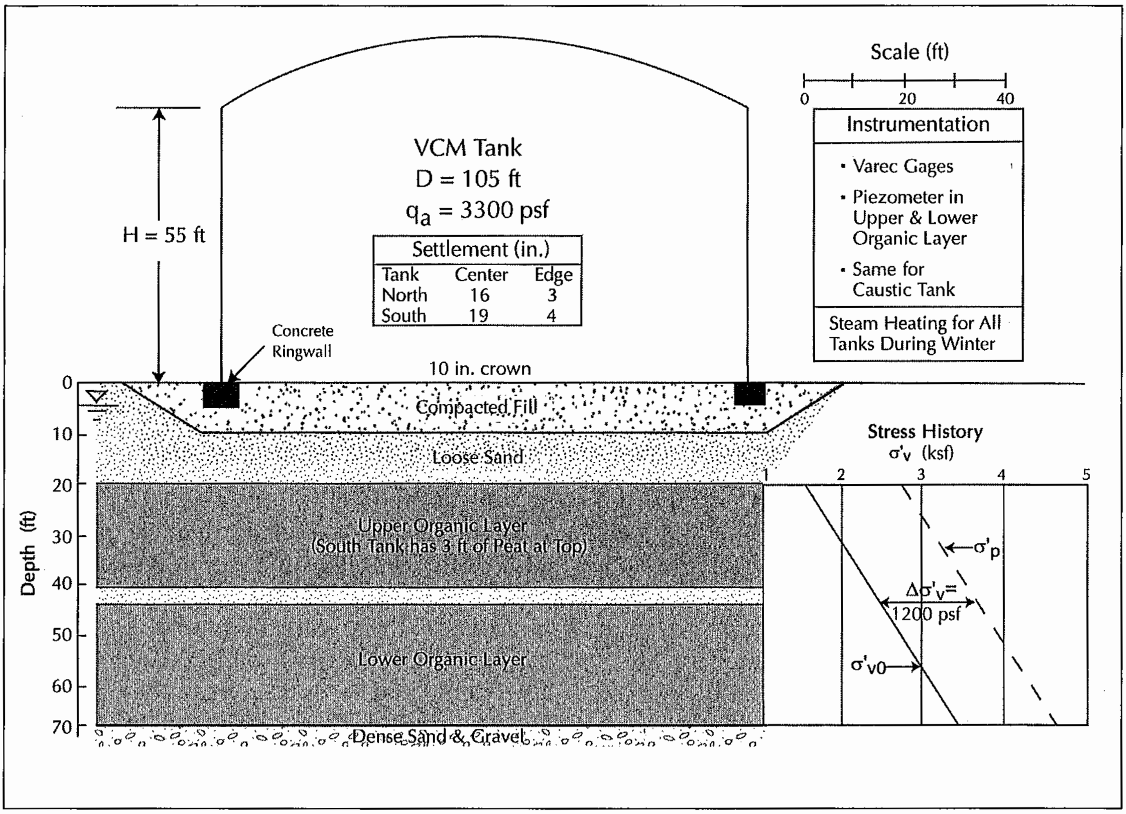

FIGURE 2. Typical cross-section for the VCM tanks with stress history, predicted settlements and instrumentation.

sampling for future lab testing if justified), train terminal staff in reading the piezometers and recording the exterior and interior settlements, and make continuous interpretation of the monitoring data in order to compare results with predictions and to recommend possible changes in the water testing loading rates and duration. The estimated cost for these services was $28,000 to $37,000. The EC recommended to the TO that the proposal be accepted and it also arranged for the purchase and installation of three Varec-type gages for each tank.

On July 1, the EC informed D&M that the TO had rejected the monitoring proposal and that the piezometers and Varec gages would not be installed.

During this period, the TO became increasingly concerned about escalating costs and its ability to profitably operate the terminal due to the poor foundation soil conditions. The TO and PPG never came to a final agreement, and on July 31, 1970, PPG paid the TO for its costs and resumed control of the project. Over the next several months, the cost estimate for the total project, which also included dock facilities, increased by $1.4 million over the original $7.5 million budget. Subsequent cost saving measures included the elimination of the Varec gages to reliably measure interior settlements of the tank bottoms and the elimination of steam heating ($11,700) to prevent freezing during the tank water testing program.

Water Testing Program & Revised Settlements

D&M was contacted by the EC and PPG during the fall of 1970. Because the piezometers and Varec gages had been deleted from the monitoring program, D&M emphasized the need for the immediate evaluation of tank monitoring data "to confirm that the settlements will be tolerable and that no tank distress will occur because of shearing deforma-

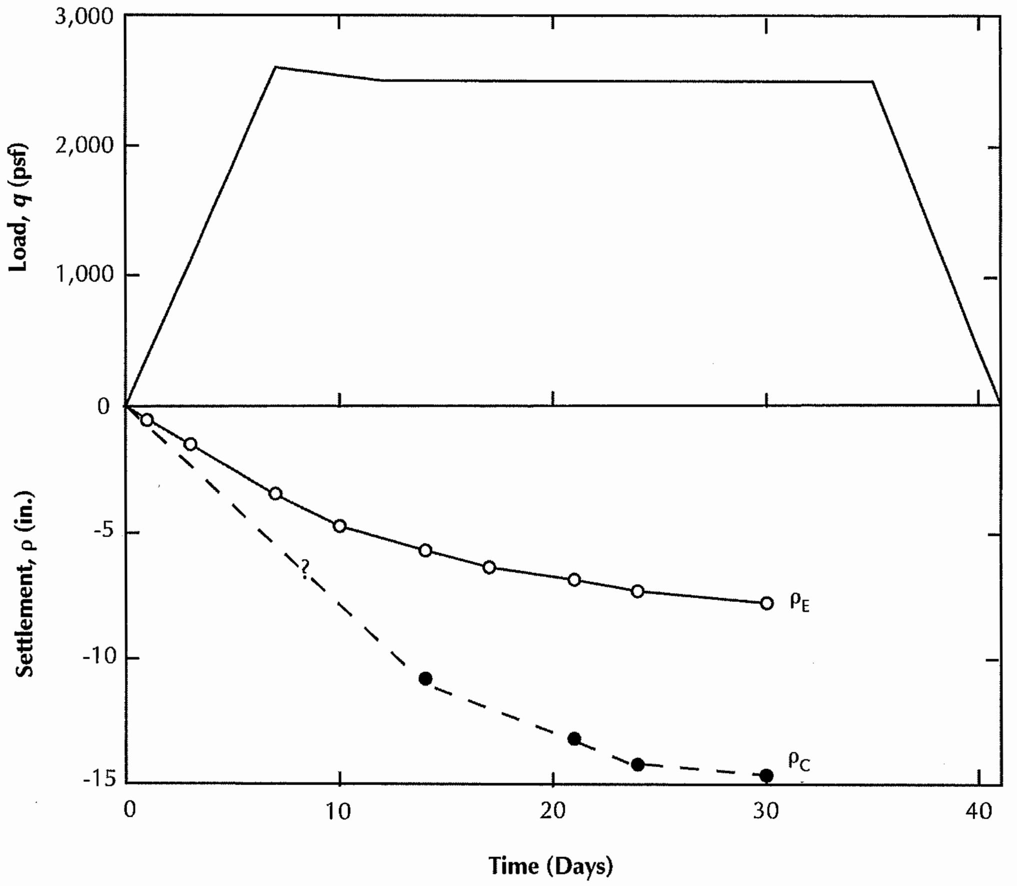

FIGURE 3. Load and settlement versus time for the first water test on the caustic tank.

tions of the supporting soils."[2] It was agreed that settlement data (two readings per week) would be phoned weekly to D&M so that "appropriate comments, conclusions and recommendations concerning future tank performance, the need and/or desirability of tank releveling, future monitoring, etc., would be provided in a timely fashion."[2]

Tank Water Testing in 1970. The DEG, MEG and caustic tanks were water tested during late 1970 for a period from thirty-one to thirty-eight days before being emptied due to the formation of an ice layer within the two smaller tanks. Edge settlements were recorded by the EC about twice weekly. Interior measurements made by PPG were less frequent because PPG used a tape and plumb bob through nozzles in the domed roof which "on windy days is difficult and sometimes not possible." (Note: Varec gages would have eliminated this problem.)

Figure 3 plots the water test data for the caustic tank, which experienced an average edge settlement of ρ_E of 8 inches and center settlement of ρ_C of 15 inches at a load of q equal to 2,500 psf. In contrast, D&M had predicted ρ_E of 3 inches and ρ_C of 14 inches after two years at q equal to 3,300 psf. The DEG and MEG tanks also had much larger and more rapid settlements than expected. Nevertheless, no settlement data were sent to D&M during these water tests.

D&M Work From January to July 1971. After finally receiving the tank water test

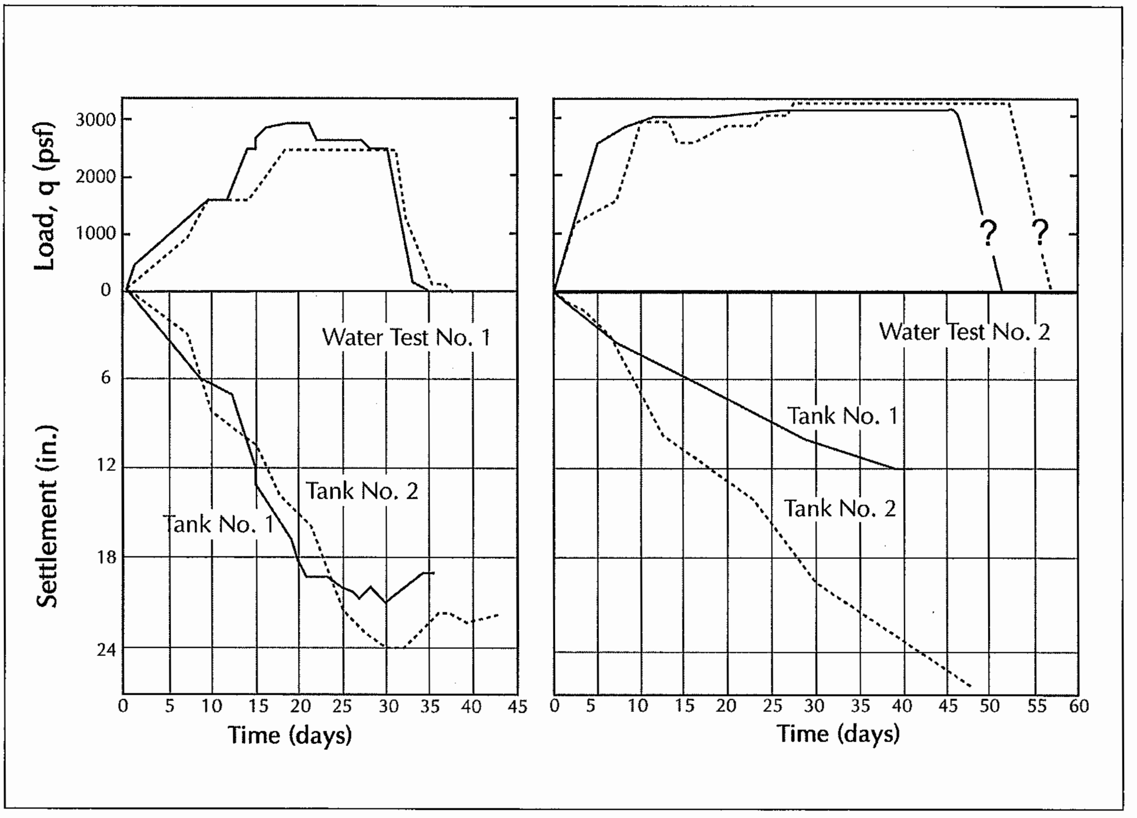

FIGURE 4. Load and settlement versus time during water tests of the two VCM tanks.

data in mid-January 1971, D&M evaluated the results and reported its findings to the EC and PPG by mid-February. D&M's observations and conclusions included the following:

- The quality of the settlement data was poor, especially regarding the interior settlements, which were needed to determine if the differential settlements were approaching the allowable limit (Varec gages were again recommended and rejected) and the loading period was too short (less than 60 percent consolidation had occurred based on plots of settlement versus the square root of time) due to the lack of steam heating to prevent freezing.
- The large settlements during water testing were attributed to the very rapid consolidation of organic soil that had a lower prestress than the 1,200 psf selected for the design, based on the reevaluation of the laboratory oedometer and strength test data. Lateral squeezing (plastic flow) due to undrained shear deformations was discounted since the foundation stability factors of safety during loading were high (greater than two). (Note: If the piezometers had been installed, Ladd and Foott concluded that they would have shown minimal dissipation of excess pore pressures and, hence, lateral squeezing, rather than rapid consolidation, caused the excessive settlements.[2])
- Although the settlements were larger than originally predicted, the center to edge differential settlements (δ equal to ρ_C minus ρ_E) were still within the tolerance of the tanks.
- New settlement estimates with a lower prestress were prepared for the second water testing of the caustic and glycol tanks (which were later confirmed in March, when the caustic tank settled less than 6 inches over forty-five days) and for

TABLE 2.
Comparison of Design Versus Water Test
Load-Settlement Data for the Caustic & VCM Tanks

Tank	1970 Design			During Two Water Tests		
	q_a (psf)	t_{90} (year)	ρ_C (in.)	q (psf)	Duration (months)	Total ρ_C (in.)**
Caustic	4,000*	2+	14	2,500	2.8	21
VCM No. 1 (North)	3,300	2-	16	2,700 to 3,100	2.0	33
VCM No. 2 (South)	3,300	1-	19	2,500 to 3,300	2.3	52

Notes: * After staged loading for 45 days at q equal to 3,300 psf
** Approximate values due to uncertain & incomplete data

the first water testing of the two VCM tanks.

Water tests of the two VCM tanks (No. 1 is the north tank and No. 2 the south) started in late February. Figure 4 plots load and centerline (ρ_C) settlement versus time. The VCM No. 1 tank initial loading of 2,900 psf was reduced to 2,500 psf because of D&M's concern that plastic flow might be occurring and both tests were terminated due to concerns about the uncertainty in, and magnitude of, the differential settlement. The edge settlements reached 9 inches for the No. 1 tank and 8 to 12 inches for No. 2, which had a slight tilt due to several feet of peat under the southern portion. The tank bottoms were mudjacked to restore the original crown after the first water tests, which had produced differential settlements of δ equal to 12 to 16 inches compared to the allowable value of 21 inches.

D&M again concluded that the VCM tank settlements were primarily due to rapid consolidation and that the prestress was even lower than the revised value. The firm used a computer consolidation model to "fit" the observed settlements to the variable applied loading. This calibrated model was then used to predict settlements during the second water testing to approximately full loading of q_a equal to 3,300 psf. Figure 4 plots the results for the second water tests, where the last reported centerline settlements reached about 12 inches and 26 inches for the No. 1 and 2 tanks, respectively, about one week before the end of loading (the unloading schedule also was incomplete). The average edge settlements after unloading were about 8 inches for No. 1 and 11.5 inches for No. 2. The collective settlement data agreed reasonably well with predictions from the computer model, which D&M then used for estimates of the residual consolidation settlements expected to occur when the tanks were put in service.

Table 2 compares D&M's design predictions with measured behavior during the two water tests of the caustic and the two VCM tanks. In a period of only two to three months, the tank bottom settlements were roughly double those predicted to occur after one to two years at water testing loads less than the full design load (especially for the caustic tank). D&M attributed this large discrepancy to the organic layers being more compressible (less prestress) and consolidating more rapidly than originally thought. Whether or not this conclusion was reasonable based on the available data became a topic of debate during the litigation. In any case, D&M encountered numerous problems during its evaluation of the water testing results. In addition to removing the piezometers from the monitoring program, which would have clearly negated the rapid consolidation hypothesis, D&M had to interpret incomplete data of dubious quality (*e.g.*, readings too infrequent, questionable measurements of bottom settlements, incomplete documentation of loading histories and problems with being furnished data in a timely fashion). Moreover, D&M's contract was terminated by PPG prior to the second VCM water tests in order to save costs. After strong objections, D&M was reinstated with an added budget of $3,000, which brought the total to $19,000.

Events From Fall 1971 to Early 1972. After completing the VCM water testing in mid-1971, the tank bottoms were mudjacked for a second time to restore the original crown (and, hence, the design differential settlement tolerance of 21 inches), the connecting pipes were readjusted and the tanks were declared safe by a metallurgical consultant (Battelle) after an inspection of the bottom welds. The caustic tank also was mudjacked (for the first time). The tanks were put in service near the end of 1971 after PPG finally agreed to install five Varec gages in each of the VCM and caustic tanks in order to accurately measure in-service bottom settlements.

During this period, PPG sold the facility to a second terminal operator for $9 million, which covered PPG's cost — of which some $235,000 was attributed to the "unpredicted and excessive foundation settlement problems."[2] As part of the sales agreement, PPG had to assume responsibility for the repair or replacement of any of the tank foundations that were found to be defective within five years after the sale. PPG informed the new owner of the prior history of the tanks and the need to carefully monitor their performance and report the results to PPG.

PPG wrote to D&M in February 1972 about the soil settlement problems and PPG's responsibility for the performance of the tank foundations until the end of 1976. The letter stated that PPG felt that "there have been several significant deficiencies in the performance of Dames & Moore . . . on this project," leading to costs that were "extremely high compared to our past experiences on other similar projects." The letter concluded by saying that after evaluating actual tank settlements versus D&M's predictions, PPG would wish to discuss "the entire Soils Program . . . with Dames & Moore, especially in the areas of financial and liability matters." D&M did not respond to PPG's letter.

Performance & Piling of the VCM Tanks

In-Service Performance From 1972 to 1974. Due to VCM production problems in Puerto Rico, the two VCM tanks were never loaded to their design capacity of 3,300 psf. The maximum load rarely reached 2,000 psf (60 percent of design load), with the loadings typically being only 1,000 psf (±500 psf). Interior (ρ_C) and edge (ρ_E) settlements were recorded approximately monthly and by the end of 1974 had reached the values summarized in Table 3, with resultant differential settlements (δ) of only several inches. These settlements were amazingly close to those predicted by D&M, but this was entirely fortuitous since the actual maximum loads were only about half of those used for the settlement predictions.

During this three-year period, PPG twice contacted Battelle to review the settlement data and inspect the exterior of the tanks. Battelle concluded that the tilt of the VCM No. 2 tank was well within allowable limits and the tank bottom was not being overstressed. However, Battelle noted that the connecting pipework had to have sufficient flexibility to avoid overstress as the tanks settled.

Events During 1975. By the end of 1974, the VCM production problems were largely resolved and, hence, it was desirable to fill the tanks to near full capacity. PPG's Engineering Department, which still did not have anyone versed in soil mechanics or foundation engineering, was charged with evaluating the ability of the tanks to operate safely with higher loads. In early January, department staff decided to perform a test by pumping VCM from the north (No. 1) to the south (No. 2) tank and over the period of January through March the VCM No. 2 tank experienced edge and differential settlements of about 1.3 and 1.0 inches, respectively, at q approximately at 2,400 psf. The total differential settlement, δ, was

TABLE 3.
Comparison of Measured Load-Settlement Data From 1972 to 1974 Versus D&M's Final Predictions

Tank	Measured (Predicted by D&M)			
	q_{max} (psf)	ρ_C (in.)	ρ_E (in.)	δ (in.)
VCM No. 1 (North)	2,000 (3,300)	6 (5 ±3)	4 (3 ±2)	2 (2 ±1)
VCM No. 2 (South)*	2,000 (3,300)	10.5 (10.5 ±4)	6 ±1 (4.5 ±2)	4 to 5 (5 ±4)

Note: * Range in measured & predicted settlements are due to the presence of a peaty layer under the southern portion of the tank.

now approximately 5 to 6 inches compared to the allowable of about 19 inches (2 inches less than the initial 21 inches due to a smaller crown after the last mudjacking in 1971). Although the settlements were far less than experienced during the water testing, PPG was concerned about the possibility of the tank bottoms rupturing due to crimping over their concrete ring walls. PPG recognized the need to inspect the tank bottoms to access this danger.

In early January of 1975, D&M was asked to evaluate the in-service settlement data and to comment on the on-going load test of the VCM No. 2 tank. After reviewing the data (and also meeting with the author for several hours), D&M concluded that "it was not evident why the tank movements are greater than anticipated" and recommended that instrumentation (piezometers, slope inclinometers and deep settlement points) be installed to check if the settlements might be due to "creep" of the foundation soils.[2] D&M recommended that the VCM No. 2 tank loading be kept at 2,400 psf — *i.e.,* no additional loading until the actual behavior of the foundation soils could be ascertained from the instrumentation. D&M's January 27 proposal for the field instrumentation and analyses was rejected, presumably due to the cost (near $50,000) and its four-month evaluation period, plus PPG's lack of confidence in D&M's ability.

In March 1975, PPG contacted a second geotechnical consultant (McClelland Engineers, Inc., from Houston, Texas) for a separate evaluation of the tank settlement problems and recommendations for what to do about the tank foundations. McClelland's $2,500 proposal was rejected.

During this three-month period, an in-house study by PPG had looked at several options. These options included:

- limiting the tank loadings, which would require a new VCM tank;
- installing a reinforced concrete slab under the tanks; and,
- supporting the tanks on a pile foundation.

The study was apparently driven by concerns about possible crimping of the tank bottoms near the concrete ringwall, the effect of higher loads on future settlements and PPG's responsibility for the tank foundations until the end of 1976.

In any case, in mid-April, PPG's Central Engineering staff recommended that both of the VCM tanks be placed on pile foundations at an estimated cost of $1.6 million. The VCM No. 2 tank was emptied in May and inspected by Battelle, which found "no evidence of any sharp bending which might cause weld cracking" — *i.e.,* there was no crimping near the ringwall.[2] Nevertheless, the south tank was moved by airflotation in order to install a pile foundation, followed by the north tank at a total cost of $2 million.

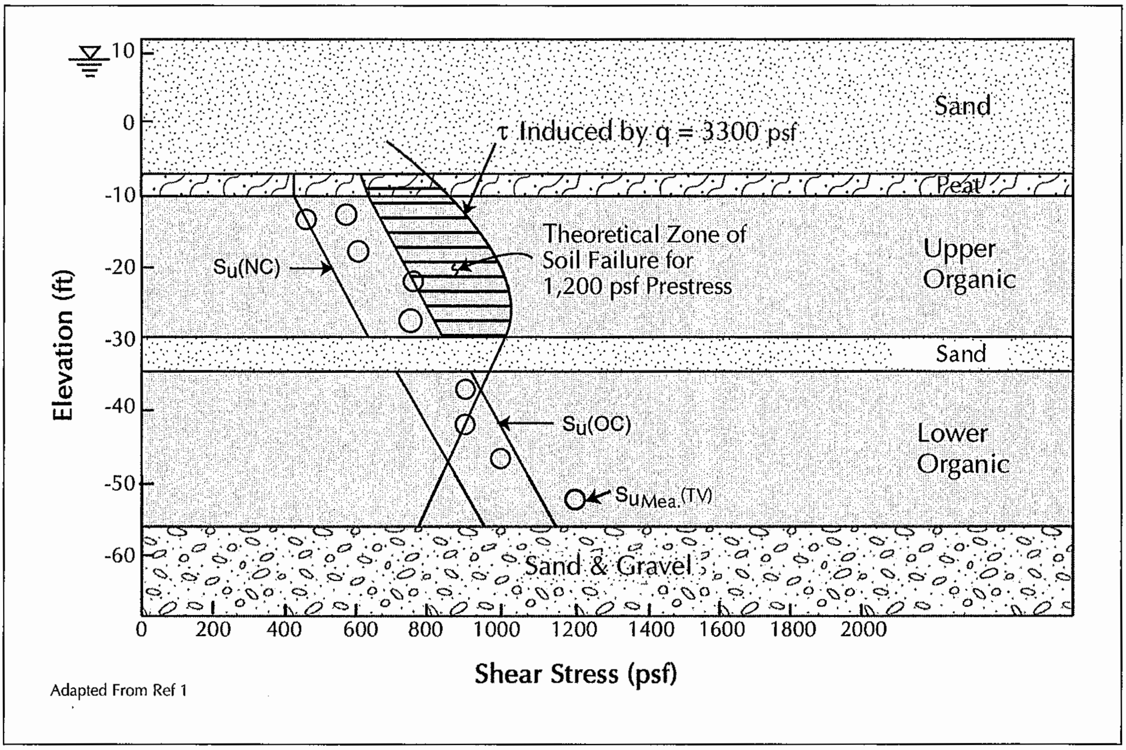

FIGURE 5. Shear stress increase and shear strength versus depth under center of VCM tank No. 2.

This cost was then passed on to D&M in the form of a lawsuit.

The Litigation

PPG filed suit in federal court in the fall of 1976 to recover its extra cost incurred by relying on D&M's recommendations. The suit alleged that D&M was negligent in the practice of soil engineering and in misrepresenting the accuracy of the tank settlements (*i.e.*, the estimated ±25 percent accuracy).

During the next two years, persons involved with both sides of the suit were deposed. D'Appolonia Consulting Engineers, Inc. (DCE), was hired by PPG as its geotechnical expert witness and filed its report in October 1977. Geotechnical expert witnesses for the defense filed their reports in August 1978. These consisted of two reports by Dr. Harl P. Aldrich, Jr. — one on the state-of-practice for the foundation design of steel storage tanks and a second on the need for piling the VCM tanks — and one by Ladd and Foott.[2-4] The latter detailed the project history, evaluated D&M's work, discussed the cause of the large settlements and the need for piling, and rebutted many of the criticisms contained in the DCE report.

The court trial was held in the Camden, New Jersey, Federal Court with a jury of six lay persons over a period of six weeks from February to March 1979.

PPG's Allegations of Negligence & Misrepresentation. There were three principal components of PPG's basic position:

- PPG had relied on D&M's settlement predictions and considered the "±25 percent estimated accuracy" to be a guarantee that included both consolidation and plastic flow (lateral deformations due to local overstressing of the foundation soils). The VCM tanks settled several feet more than predicted by D&M in 1970 (Tables 2 and 3 add up to an extra 1.9 feet for tank No. 1 and 3.6 feet for No. 2).
- D&M's proposed instrumentation during water testing was of "academic interest";

otherwise D&M would have strongly objected when it was deleted.
- The piling was justified since PPG needed full tank capacity, which would have created the danger of a rupture of the tank bottom. D&M could not predict when the settlements would stop and PPG worried that the settlements would continue indefinitely.

The detailed report by PPG's geotechnical expert put forth the opinion that much of the tank settlements during water testing was the result of lateral deformations due to plastic flow of the organic silt layers.[1] It contended that D&M was negligent in its estimation of the likelihood of these settlements occurring and in failing to identify them when they occurred during the water testing. DCE further contended that whenever *any* local overstressing of soil below a tank occurred, the profession would normally expect that large and unpredictable plastic flow settlements could take place. And this situation would arise whenever the FS was less than 2.0.

Figure 5 was used to illustrate the extent of local overstressing at the centerline of VCM tank No. 2. It shows the soil profile, the computed undrained shear strength (s_u) for the organic layers if they were normally consolidated (a lower limit) and with a prestress of 1,200 psf (as assumed by D&M and essentially endorsed by DCE), and measured values of s_u from D&M's laboratory Torvane tests. For an allowable tank loading of q_a equal to 3,300 psf, for which DCE computed a FS of 1.45, the line labeled τ is the theoretical shear stress obtained from elastic stress distribution. Hence the shaded area represents the theoretical zone of soil failure (for a 1,200 psf prestress) — *i.e.*, the zone where plastic flow would occur. DCE further maintained that such local overstressing can lead to "progressive failure" and ultimate failure of the tank. The DCE report also stated that:[1]

> *For the conditions that existed at the Mantua site, a safety factor of 3.0 appears to be an appropriate recommendation. Many articles published in the geotechnical literature prior to 1970 would also support this value.*

The DCE report also made many detailed criticisms of D&M's work, including: insufficient number of deep borings, undisturbed samples, and laboratory tests; and inappropriate testing procedures and interpretation of the test data. Moreover, even though the piezometers had not been installed, the water test settlement data were sufficient to show that significant plastic flow (lateral deformations) was occurring.

D&M's Defense Against Professional Negligence & Misrepresentation. D&M's basic position was that the settlement estimates, with the ±25 percent estimated accuracy, applied to normal consolidation movements. The estimates did not include any allowance for plastic flow movements, especially since methods for predicting their magnitude did not exist at that time. D&M believed that it had made the possibility of additional large and unpredictable settlements due to plastic flow at loads above q at approximately 3,000 psf very clear in the May 1970 meetings and reports. It was because of this possibility, and to check predicted tank behavior, that extended water tests and instrumentation, especially the piezometers to measure in situ excess pore pressures, were recommended, agreed to and included with the permit submittal. D&M contended that the failure to implement this instrumentation program was a major contributing cause of its inability to fully explain the observed behavior, and of the ultimate and unnecessary decision to place the VCM tanks on piles.

The reports by D&M's geotechnical experts contended that D&M's initial foundation investigation and recommendations were reasonable and conformed to accepted standards for such work.[2-4] The use of factors of safety in the range of 1.2 to 1.5 was considered normal practice with flexible-bottomed steel tanks, for which the applied loads are precisely known, in contrast to foundations for building and bridges. (Note: The FS range of 1.2 to 1.5 was specifically quoted in Haley & Aldrich, which summarized that firm's practice based on seven soft ground projects with steel storage tanks between 1965 and 1970.[3]) D&M's use of a FS at the top of this range was appropriate for instrumented tanks containing hazardous materials at a new site. The reports considered the use of a one-dimensional consolidation model as being common practice for predicting ultimate tank settlements. And the resulting estimates should be reasonably accurate, often within about ±25 percent, although this range could not be guaranteed.

Ladd & Foott made a thorough analysis of the settlement behavior of the tanks.[2] This analysis benefited from extensive ongoing research at the Massachusetts Institute of Technology (MIT) regarding the likelihood of excessive settlements occurring due to undrained shear deformations and the role of plastic flow on their magnitude.[5,6] They concluded that the large settlements observed during the water tests were primarily due to undrained shear deformations (as did DCE), but the principal cause was an unusually low ratio of undrained Young's modulus to undrained shear strength (E_u/s_u) for the highly plastic, organic foundation soils, rather than plastic flow per se as proposed by DCE. The report also concluded that the in-service tank settlements occurred mainly due to consolidation, but at a rate faster than expected from the laboratory consolidation tests, and that the settlements had stabilized (essentially leveled off) for the caustic tank at q equal to 3,300 psf and for the VCM No. 1 tank at q equal to 2,000 psf.

The D&M experts contended that the data available from the water tests (*e.g.*, such as shown in Figures 3 and 4) indicated that the settlement rates were decreasing with time, which is characteristic of consolidation behavior. Hence D&M's interpretation of the data as rapid consolidation of soil having a lower prestress than initially selected was reasonable. (Note: As previously mentioned, the factor of safety of the caustic tank was calculated to be greater than 2.0, which would preclude plastic flow based on the then-available analysis techniques.) Moreover, had the recommended piezometers been installed, the lack of dissipation of excess pore pressures during the settlement periods would have clearly shown the occurrence of excessive undrained shear deformations rather than rapid consolidation.

D&M's experts did not consider it necessary to pile the VCM tanks in 1975. At the time of the piling, the differential settlements were less than one-third of the allowable value and it was not reasonable to expect "sharp bending" near the ring wall, as later proven by inspection of the tanks when emptied. With staged loading of these tanks to a q_a of 3,300 psf, long-term consolidation settlements of one to two feet would be expected, which may have required one more recrowning of the tank bottom via mudjacking (as done after the first and second VCM water tests).

Finally, D&M's defense team believed that PPG was guilty of "contributory negligence" (*i.e.*, PPG exacerbated the problem), which if proven would have prevented PPG from collecting any damages. Specifically, PPG's failure to implement the instrumentation program was a major contributing cause leading to unnecessary piling because:

- D&M was not involved during the first water tests of the caustic and glycol tanks, which, combined with no steam heating to prevent icing, caused the premature termination of the water tests.
- The lack of Varec gages led to incomplete and inaccurate measurements of the interior bottom settlements, and, hence, uncertainty in the differential settlements.
- The lack of piezometers led to the misinterpretation of the settlement data as rapid consolidation. The piezometers would have shown minimal dissipation of excess pore pressures, which would have indicated large settlements caused by undrained shear deformations (lateral squeezing) rather than consolidation. If this information had been available, D&M would have recommended loading in stages (which was recognized as a contingency plan), which would have increased the undrained strength and stiffness of the organic soils and thereby led to significantly less lateral squeezing and, hence, smaller total settlements.

The Trial

It should be noted that this was the author's first experience as an expert witness. I thought we had a very solid defense, but my naivety caused a lack of understanding of the adver-

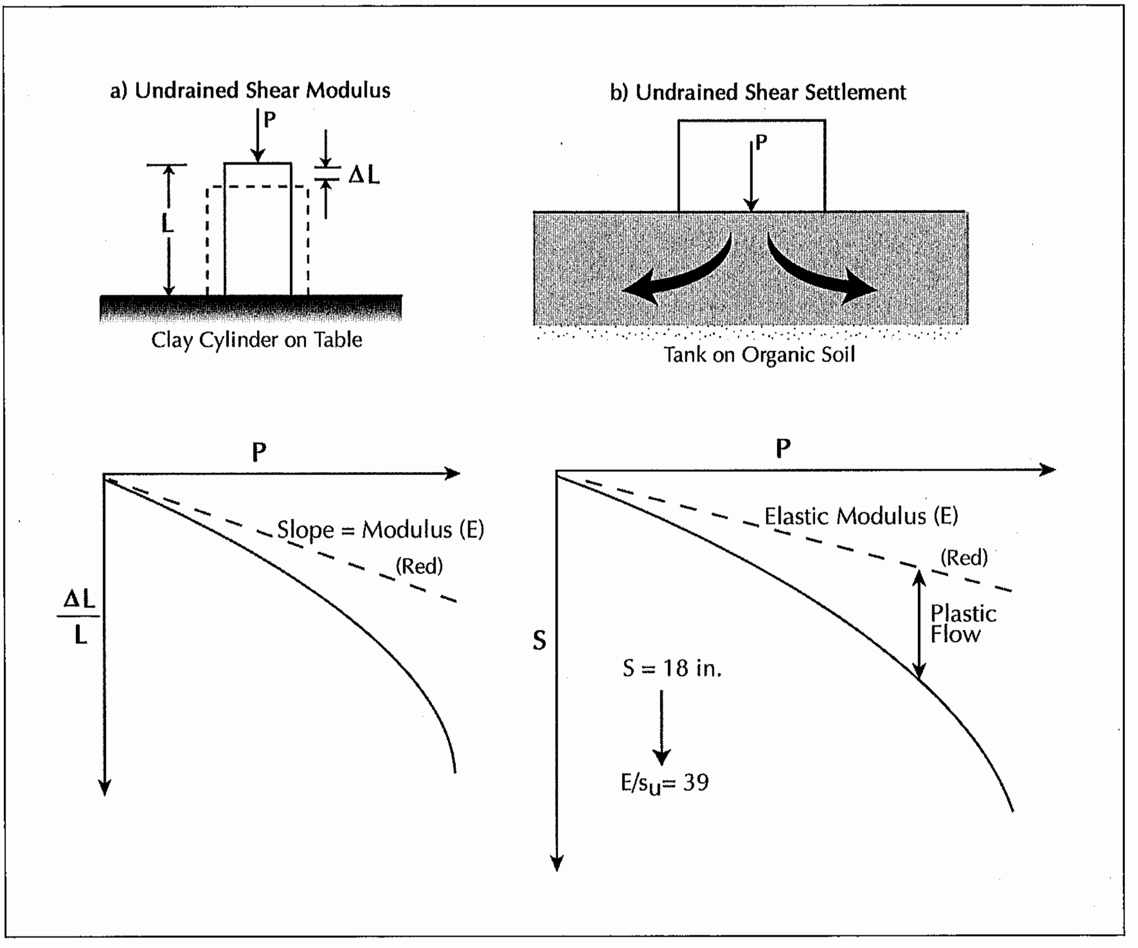

FIGURE 6. Sketches used to explain modulus and undrained shear settlement with plastic flow.

sarial system of justice in the United States (*i.e.*, that lawyers are hired to win the hearts and mind of the jury in order to win the case for their clients). Nor did I appreciate how important the competence of the judge and lawyers was to the final outcome. (Note: Remember this trial occurred well before the televised trial of O.J. Simpson.)

PPG presented its allegations over a period of four weeks. It was easy to prove that the tanks had settled much more than predicted (and certainly far more than the "±25 percent estimated accuracy"), to document the extra costs incurred during water testing and piling, and to illustrate PPG's concerns about the safety of the VCM tanks (via internal memos, depositions, etc.). Dr. Elio D'Appolonia testified for five hours in order to cover the essence of the material contained in the 1977 DCE report. However, in this author's opinion, D&M's lawyer did a poor job of identifying major weaknesses in D'Appolonia's testimony during only three hours of cross-examination. This opinion especially applies to the concept that soft ground construction designed with a factor of safety of less than 2.0 may lead to ultimate failure due to progressive failure, which is clearly contrary to decades of experience with highway embankments, levees, preload fills, etc. The contention that D&M should have used a design FS of 3 for the tanks also defied common practice.

Dr. Foott's Testimony. D&M's defense relied primarily on testimony by the authors of the three geotechnical expert witness reports. Dr.

Roger Foott went first with an analysis of the in-service tank performance and why piling was not necessary, but his cross-examination did not go well for the defense. Since Dr. Foott had been sitting with the D&M lawyers during the trial, his testimony was viewed as not meeting the objectivity required of an expert witness.

Ladd's Direct Testimony. My first direct testimony, which lasted two hours, was not well suited for a trial in that I basically gave a series of lectures in response to four principal questions that the D&M lawyer had told me he would ask:

- What are the usual steps in geotechnical design of tank foundations?
- What did you examine, find and conclude regarding D&M's work in 1970?
- What do you have to say about D&M's conduct during 1971 (my reply included an explanation of why the lack of piezometers led to D&M's attributing the excessive settlements to consolidation rather than plastic flow)?
- What do you think caused the excessive tank settlements?

(Note: On the day prior to my testimony, I had prepared 20 pages of handwritten notes that covered these four questions)

Figure 6 shows two sketches that I used in response to the last question. Part (a) attempted to explain the concept of Young's shear modulus (E). Part (b) was used to illustrate the concept of lateral squeezing and the fact that the value of E was far more important than plastic flow per se as proposed by DCE. I then used the technique presented by D'Appolonia *et al.* to backcalculate the value of E/s_u from the first water test of VCM No. 2.[5] The resulting E/s_u of 39 was an order of magnitude lower than quoted from ten case histories cited in that study and, hence, the highly unusual organic soil at the site represented a unique case in the annals of geotechnical engineering.

After being cross-examined for the entire next day, I was again put on the stand for redirect testimony. This time the defense lawyer posed a series of specific questions, mostly regarding how I obtained the E/s_u of 39, why this was so unusual, and why the piezometers contributed to the problem. This testimony was, I believe, more effective in defending D&M.

Ladd's Cross-Examination. I soon learned that the objectives of this exercise were to discredit my expertise (which was not successful since I had a thorough knowledge of the technical issues), catch inconsistencies in my testimony (somewhat successful) and to confuse me and the jury.

The lawyer asked me to define the following terms and explain related questions (mostly from Ladd and Foott):[2] undrained settlement; plastic flow; the difference between 1-, 2- and 3-dimensional loadings; the difference between secondary compression and undrained creep; to establish whether undrained creep is plastic flow; to delineate what mechanics occur in soil during plastic flow, among other things. These questions unsuccessfully attempted to confuse me.

Since my undergraduate thesis was included in PPG's list of documents, I had looked at the appendices but not the text.[7] The lawyer read statements from the thesis trying to establish that a FS of 3 was used for the design of the tanks, that the profession knew about plastic flow before 1955 and that secondary compression settlements can be fairly large with organic soils. I considered this line of questioning really hitting below the belt since I knew very little about soil mechanics at that time (having taken only one undergraduate course on the subject) and received only a B grade on the thesis.

The lawyer proceeded to list twenty-five articles that discuss "plastic flow, strength loss and progressive failure and closely related phenomena: creep, local yielding, local shearing and strain softening." After that, he asked me which ones "were relevant to this case." I had made notes on all twenty-five and thus easily responded to the first several articles. He then changed the question to, "was the concept of plastic flow discussed" and I again answered. He finally changed the question to whether or not the words "plastic flow" were used in the article. I was now stumped since different authors used different terms.

When asked if the piezometers were essential to the project, I replied that D&M correctly recommended that they be installed and, if they had been, then D&M would have recognized that the excessive settlements during water testing were primarily caused by undrained shear deformations, rather than rapid consolidation of soil with a lower prestress than originally assumed. The judge asked, "Would that have stopped the tanks from settling as much as they did?" and I answered that "that is not the issue . . . because we know that piezometers do not stop the tanks from settling." That was a poor answer. The correct answer, given later on redirect, was: Yes, the piezometers would have reduced the settlements because D&M then would have recognized the problem (*i.e.*, large undrained shear deformations) and, therefore, would have recommended staged loading of the tanks (*i.e.*, preloading) in order to increase the stiffness of the soil via consolidation and, hence, end up with smaller final settlements. The judge then asked if they would have exceeded those originally predicted by D&M (*i.e.*, the issue of the ±25 percent accuracy). I had to agree that they would have, due to the very low E/s_u of the soil, but with magnitudes much less than had occurred. (Note: If it were established that PPG's deletion of the piezometers had contributed to the problem, then PPG would have been guilty of "contributory negligence" and could not have been awarded any damages).

Since I testified that the uniquely low modulus of the soil (the E/s_u of 39) caused the excessive settlements rather than negligence by D&M, the lawyer posed a long series of questions along the following lines (remember that the jury was composed of six lay persons):

- We're talking of organic silt having a low modulus. We could go out to Paulsboro with a shovel, dig a hole and have a pile of this dirt sitting in the courtroom. What makes this soil suffer from this magical thing that leads to a low modulus?
- Is the soil soft and squishy like baby food?
- Is it like stepping into quicksand?
- How does this low modulus affect what happens when you drive a stake into the ground?
- What is low modulus: Is it the color of the soil, or the weight of the soil or the amount of water in the soil or what?

By this time I was getting rather frustrated and I again referred to the sketch I had prepared for the trial, which is shown in Figure 6a, and answered the last question by stating, "It is the slope of the plot of pressure versus strain when you load the soil. It would be the red line marked modulus *E*." The lawyer then replied, "There was no slope out there at the Paulsboro site. You know that, don't you, that this was level ground?" (Note: I thought that the lawyer's response was a masterful attempt to thoroughly confuse the jury.)

Dr. Aldrich's Testimony. Dr. Aldrich then detailed the state-of-practice for the design of tank foundations and explained why he believed that it was not necessary to pile the VCM tanks. During the former, he stated that whereas building foundations commonly used stability factors of safety of 2.5 to 3.0, lower values of FS from 1.2 to 1.5 were accepted practice for tanks because:

- the maximum load is precisely known;
- tanks can be filled to the maximum design load during water testing; and,
- since the first two points confirm tank safety, lower design factors of safety can result in significant cost savings.

As readers who personally know Dr. Aldrich would expect, his testimony was clear and concise, and easily withstood two hours of cross-examination even though it clearly refuted DCE's position regarding design factors of safety.

Charge to the Jury & the Outcome

The judge's charge to the jury posed three principal questions.

- Was D&M negligent in the practice of geotechnical engineering and in misrepresenting the accuracy of its predicted tank settlement?
- If so, was that negligence a proximate cause of PPG's damages?

- What is the amount of damage incurred by PPG?

The judge *refused* to allow the jury to consider PPG's possible contributory negligence by not installing the recommended instrumentation for monitoring tank performance (most especially the piezometers) and by not involving D&M in a timely fashion during the initial water testing of the tanks.

The jury found D&M guilty of negligence. The "±25 percent accuracy" was thought to be the major problem by the defense lawyers since this was the expected margin of error set by the geotechnical consultant. PPG was awarded damages of $1,883,000, plus $378,000 in interest. D&M appealed the verdict primarily on the basis that there was ample evidence of possible contributory negligence by PPG for this charge to have been considered by the jury. The case was settled prior to the appeal being heard for $1.6 million.

The D&M defense cost over $500,000.

Lessons Learned

There were a number of things that D&M could or should have done to possibly avoid the unfortunate outcome of the project or to be in a stronger position during the litigation. This "discussion" is largely based on the commentary set forth by Foott and in ASFE *Case History No. 20.*[8,9]

Spell Out the Risks of Excessive Settlements More Clearly. D&M clearly noted the possibility of excessive, unpredictable settlements due to plastic flow of the organic silt layers in its May 8 progress report, and most likely during the meetings of May 11 and 12. However, this topic was not discussed in its May 15 final report, which was a mistake. The final report also should have stated that the "±25 percent accuracy" of the estimated settlements applied only to those caused by consolidation and did not include possible increases due to undrained shear deformations (which could not be predicted at that time). Ideally, the report also should have spelled out the possibility of the need for preloading via staged filling for the VCM tanks, as was done for the caustic tank having a higher design load (as per the data presented in Table 2). However, if the consultant's recommendations become overly qualified and cautious, they then tend to lose their substance.

Explain More Clearly the Benefits of Instrumentation & Involvement by the Geotechnical Engineer During the Water Testing Program. The final report and instrumentation proposal should have explained in more detail how the piezometers would be used to assess the rate of consolidation and, hence, help to distinguish between settlements resulting from dissipation of excess pore pressures (*i.e.*, consolidation) versus those caused by undrained shear deformations (which includes plastic flow). Such analyses require geotechnical expertise and if the piezometers had been installed, D&M would not have interpreted the very large settlements during the water tests as rapid consolidation of soil with a lower prestress than originally assumed. Furthermore, D&M presumably then would have recommended prolonged water testing in stages in order to strengthen the soil and, hence, reduce settlements due to undrained shear and plastic flow.

Complaining When the Client Does Not Follow the Consultant's Recommendations. During the trial, PPG maintained that if the instrumentation program was so critical, why did not D&M complain when it was scrapped? D&M did strongly complain about the lack of Varec gages to obtain direct readings of tank bottom settlements (which was again ignored) and the incomplete and poor quality data obtained during the first water tests in late 1970. But whether or not the piezometers were "essential" became a major and complex issue during the trial (*e.g.*, the judge's question to me about whether the piezometers would have reduced the settlement of the tanks). Although the piezometers were certainly desirable, the tanks had fairly conservative factors of safety and they would have been water tested with the monitoring of settlements — *i.e.*, the original design did not require staged loading to strengthen the foundation soils (although the caustic tank did have an intermediate loading period). It also should be noted that many preloading projects rely only on settlement data to determine when the preload can be removed. Nevertheless, it would have been helpful for the defense if D&M had advised PPG of the added risk posed by not having piezometer data to help interpret the settlement records.

Problems With Interpreting Poor Data in a Short Time Period. The first water test data in late 1970 (see Table 1) were not sent to D&M on a weekly basis as promised, the data were incomplete and of questionable accuracy (*e.g.*, the results in Figure 3) and the tests were terminated prematurely due to concerns about freezing (steam heating was not used as recommended by D&M). Should D&M have refused to analyze the data? Probably not, but D&M could have made it clear that the results of its analyses might be misleading due to the questionable validity and incomplete nature of the data. On the other hand, D&M believed that its interpretation of the large settlements as being caused by the rapid consolidation of soil with a lower prestress to be quite reasonable, so why dwell on possible shortcomings? DCE did maintain during the trial that D&M should have recognized the dominant role of plastic flow, even without the piezometers, although this contention was disputed by the defense.

Responding to PPG's Letter of February 1972 to D&M. This letter criticized the quality of D&M's work and basically threatened to discuss financial and liability matters after evaluating the in-service tank settlements. D&M never replied. Although understandable given PPG's history of inappropriate actions and the insulting nature of the letter, D&M obviously should have taken steps to understand the reasons for PPG's displeasure and attempted to resolve them, perhaps by involving third-party mediation.

Summary

The author's experience as an expert witness has been limited to some half-dozen or so major litigations. In each case, I was given sufficient time to study all geotechnical aspects in my areas of expertise in great depth. This preparation is essential, since it ensures that the client's lawyer clearly understands the expert witness's opinions, including those opinions that may not help the client's case. After deciding which items that will be testified to, it is wise to develop a detailed outline of the specific questions to be posed and the answers. My first direct testimony in the trial described here was not appropriate because the questions were far too open-ended. An expert witness also needs to discuss with the lawyer questions that may be raised during cross-examination concerning issues where the expert's opinion may not support the client. When sworn in, the expert is told to tell the truth, the whole truth and nothing but the truth. I have no problem with the first and third requirements, but do worry about "the whole truth." I handle this dilemma by providing brief answers to specific questions and do not feel obligated to volunteer information that will help the other side — that is the job of the opposing lawyer.

ASFE has published an excellent reference for engineers asked to serve as expert witnesses.[10] It starts with an overview of the judicial process and then gives detailed guidance about providing forensic services, including preparation for depositions, testimony and cross-examination. I wish it had been available before this trial.

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maturely in 1994 of leukemia. Dr. Marika Santagata, a former Ph.D. candidate at the Massachusetts Institute of Technology (MIT) and now Assistant Professor of Civil Engineering at Purdue University, prepared the final version of the PowerPoint presentation used for the Casagrande Lecture. She is indeed a good friend. Gretchen Young, former S.M. student at MIT, typed the manuscript, prepared the final figures and provided helpful comments on the draft. Her assistance is appreciated, as always. Finally, Dr. Harl Aldrich's review of this article led to numerous editorial improvements. He also helped steer the author toward geotechnical engineering during his senior year at MIT via part-time laboratory and field work for two oil storage tanks that formed the basis for his S.B. thesis. References 5 and 6 were outgrowths of doctoral theses submitted to MIT.

NOTE — *The opinions and representations presented in this article reflect those of the author, and are not those necessarily of* Civil Engineering Practice *or the Boston Society of Civil Engineers Section/ASCE.*

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