Settlement of Ammonia Storage Tanks

Observations of data from several case studies emphasize need for more performance information and suggest that costly pile foundations are not always necessary.

M.I. Esrig and S. Ahmad
Woodward-Moorhouse and Assoc., Inc.
Clifton, N.J.

H.C. Mayo
Cooperative Farm Chemicals Assn.
Lawrence, Kans.

Studies of settlement data on three ammonia storage tanks have shown that despite large distortions of the base plate near the tank edge and substantial stresses in those plates, satisfactory tank performance has continued.

It is hoped that publication of these data will lead to reassessment of some of the design criteria now in vogue and, perhaps, to modifications in these criteria.

General criteria for tank displacements are presented in Table 1 for atmospheric tanks and for low-temperature tanks. Of special interest is the fact that the criteria for both atmospheric and low-temperature tanks are essentially identical. Apparently, the ductility necessary for the proper performance of low-temperature tanks is provided by the materials chosen for construction. Consequently, it appears reasonable to compare the observed behavior of these two types of tank.

Inherent in the criterion for settlement of the base plate is the following statement made by one tank vendor to an owner: "This settlement must occur in a dish configuration concentric with the center of the tank." It is this concept of concentric settlement which the observational data bring into sharp question.

The displacements of the base plates of ammonia storage tanks constructed at Garner, Iowa; Mankato, Minn.; and Greenwood, Nebr. were measured. Measurements of the deflected position of the base plates at the Garner and Mankato tanks were obtained after completion of the water test. Continuous measurements of the position of the base plate along a single diameter were made during the water test program at the Greenwood tank using a double fluid settlement device. Upon completion of the water test, the position of the base plate was measured in a manner similar to that used at Garner and Mankato, and these measurements were compared with the data obtained from the double fluid settlement device. The agreement between the measurements was sufficiently close to give confidence in the validity of the Garner and Mankato observations.

The final position of the base plates after the completion of the water tests was measured by entering the tank while about 18 in. of water covered the floor. By measuring the depth of the water along several diameters, and by assuming that the tank vendor had constructed the tank to the design configuration with a 9 in. center crown, the total displacements of the base plates at the end of the water test could be calculated. The displacement data are presented in a subsequent section.

Continuous profiles of the base plate displacements at Greenwood were obtained by installing 3/16-in. diameter tubing in the compacted sand beneath the insulation block and measuring the displacements using the double fluid

Table 1. General criteria for tank displacements

Criterion	Atmospheric tanks* Settlement category I	II	III	Low temperature tanks**
Maximum shell settlement, in	12	6	2	Depends on flexibility of piping.
Maximum differential settlement of bottom plate, inches in 30 ft.	2	1	½	1 in./10 ft. of radius, with maximum of 8 in.
Maximum tilt	about 12 in.			6 to 12 in., depending upon roof details.
Maximum differential settlement of shell	½ in. in 30 ft. from a tilted planar position and maximum of 2 in. in 30 ft.			1/2 to 3/8 in. in 30 ft. from a tilted planar position, depending upon ratio of diameter to height

* Esso Research & Engineering criteria (Clarke, 1971).
** Chicago Bridge & Iron criteria.

settlement device.

This is a new device for measuring settlement with a hydraulic system. It consists of a pumping circuit for filling the measurement loop with water and flushing out any trapped air, another pumping circuit for control of the principal measuring fluid (mercury), a precision pressure gage, and associated hydraulic control valves.

How the displacement device functions

The basic operation is simple. A loop of 3/16-in. tubing is filled and flushed with water, then mercury is fed into the loop. The mercury displaces the water, pushing it out of the loop and into a volume-calibrated burette on the return side of the gage. The operator controls the advance of the mercury in the measurement loop by opening or closing a control valve to the burette. Immediately below the calibrated burette, the pressure in the water line is measured by a precision gage. When the operator stops the mercury-water interface at a desired measurement point along the plastic tubing traverse, the pressure of the mercury column from the gage down to the point in the loop is read on the precision gage. The pressure establishes the elevation of the tubing at the interface location. All elevations are referenced to the reading of the gage for a position of the mercury-water interface in a horizontally-coiled length of the profile tubing on a flat steel datum plate at the terminal location.

The accuracy of the double fluid settlement device is estimated as about 1/4 in. in elevation and better than about 1 ft. in horizontal location. The manually-operated system used at Greenwood was designed and constructed by Woodward-Clyde Consultants. Cost of the entire system with automatic operation and continuous data recording is less than $10,000.

The three ammonia storage tanks for which the displacements of the base plates were obtained have storage capacity for 30,000 ton of anhydrous ammonia. The tanks at Garner and Mankato have diameters of 170 ft. and are 62 ft. high. The Greenwood tank has a diameter of 180 ft. and is 56 ft. high. The walls are supported on reinforced concrete ring walls about 7 ft. deep, with base widths of 6 to 8 ft. The base plates were to be crowned 9 in. in the center.

The subsurface conditions and the displacement data for each of the tanks are presented in the following. Only the Greenwood information on subsurface conditions was obtained by Woodward-Moorhouse and Assoc., Inc. The generalized subsurface conditions at the locations of the three sites are shown in Figure 1.

Subsoil conditions at Garner were explored by means of five borings. The upper 45 ft. of soil consists of a sandy clayey silt (identified as a glacial till) overlying very dense sand and sandy silt. The undrained shear strength of the clayey silt layer was found to be greater than 800 lb./sq.ft. on the basis of unconfined compression tests and hand penetrometer data. The clayey silt layer can be considered moderately compressible, while the soil underlying it can be considered essentially incompressible under the imposed loads. Groundwater was typically encountered at a depth of about 7 ft.

The water test was made by filling the tank with 53.5 ft.

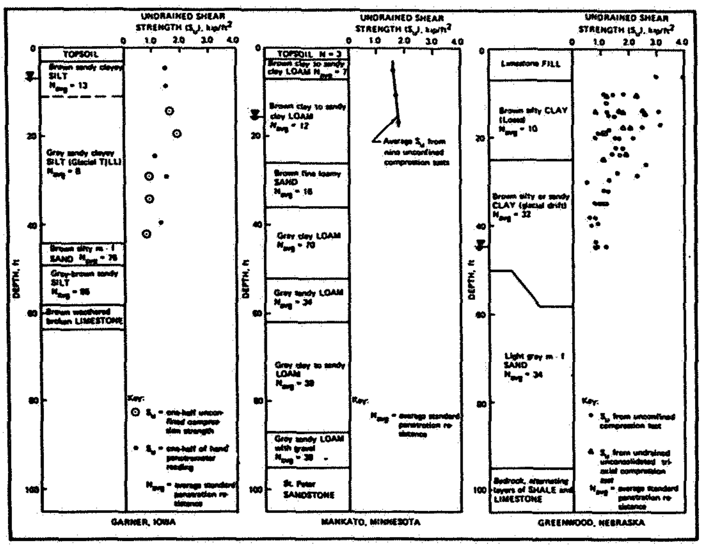


Figure 1. Generalized subsurface conditions at the locations of the ammonia storage tanks.

of water. Following completion of the water test, about 20 in. of water was left in the tank and the final shape of the base of the tank was determined by measuring the depth of water above the base plate with a ruler. These measured and inferred (computed) displacements are shown in Figure 2. A measured displacement of 5-1/4 in. (5-1/2 in. inferred displacement) was found to occur at a distance of 4 ft. from the wall of the tank, resulting in an angular rotation of about 1/9 in the vicinity of the wall. The inferred displacement near the center of the tank, relative to the ring wall, ranges from about 4-1/2 to 7 in., resulting in a maximum angular rotation of about 1/146 between the ring wall and the center of the tank.

Maximum ring wall settlements of about 3/4 in. were reported to the owner.

The subsurface conditions at Mankato were evaluated by means of five borings. The upper 25 ft. of soil, described as clay loam, can be considered moderately compressible,

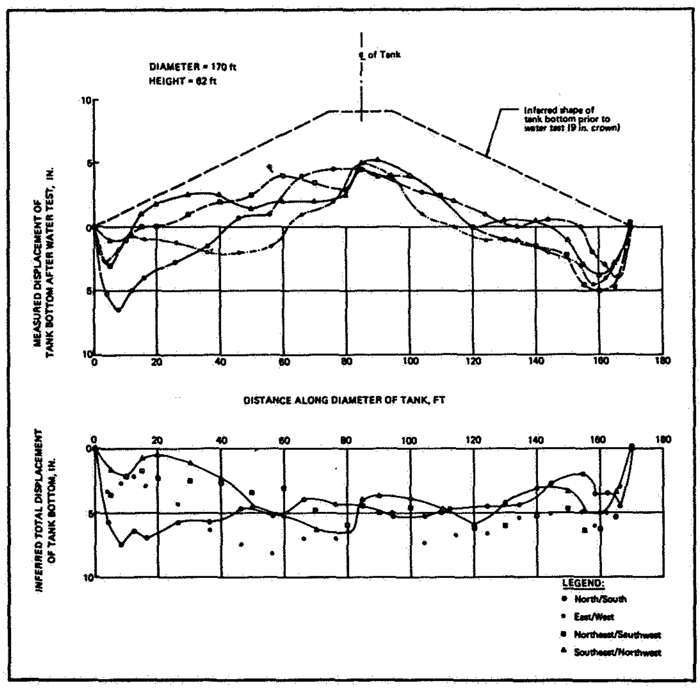


Figure 2. Measured and inferred displacement of tank bottom after water test, ammonia storage tank, Garner, Iowa.

while the sand and clay loam below this depth can be considered only slightly compressible under the imposed loads. The undrained shear strength (evaluated by means of unconfined compression tests) of the upper moderately compressible clay loam was found to range from about 1,600 lb./sq.ft. near the surface to about 1,900 lb./sq.ft. near the bottom. Groundwater was typically encountered at a depth of about 16 ft.

The water test was made by filling the tank with 52.5 ft. of water. After completion of the water test, measurements were made in accordance with the previously outlined procedure to determine the final shape of the base of the tank. These measured and inferred displacements are shown in Figure 3. A displacement of 3-1/4 in. (3-3/4 in. inferred displacement) was found to occur at a distance of 3 ft. from the wall of the tank, resulting in an angular rotation of about 1/10 in the vicinity of the wall. The inferred displacement near the center of the tank, relative to the ring wall, ranges from about 7-1/2 in. to 8-1/2 in., resulting in a maximum angular rotation of about 1/120 between the ring wall and the center of the tank.

Maximum ring wall settlements of about 1/2 in. were reported to the owner.

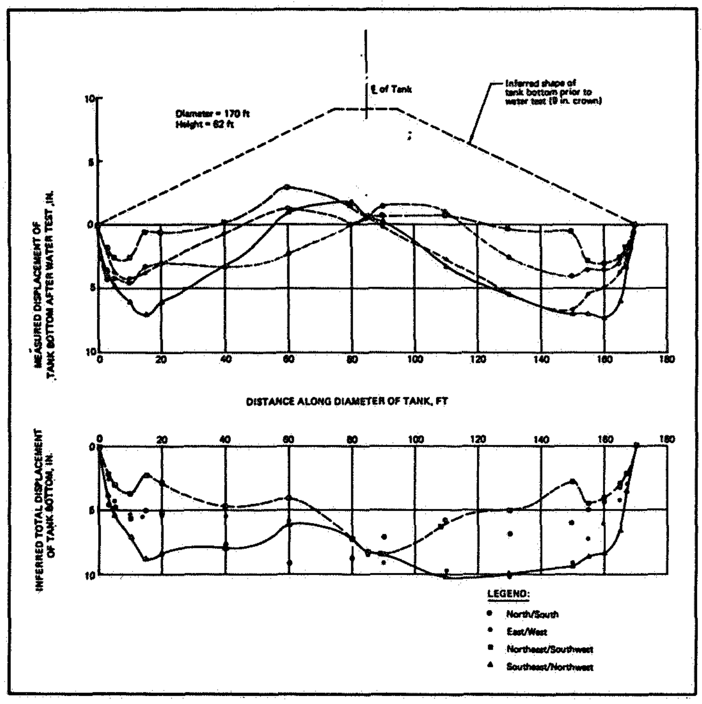


Figure 3. Measured and inferred displacement of tank bottom after water test, ammonia storage tank, Mankato, Minn.

More borings at Greenwood than other sites

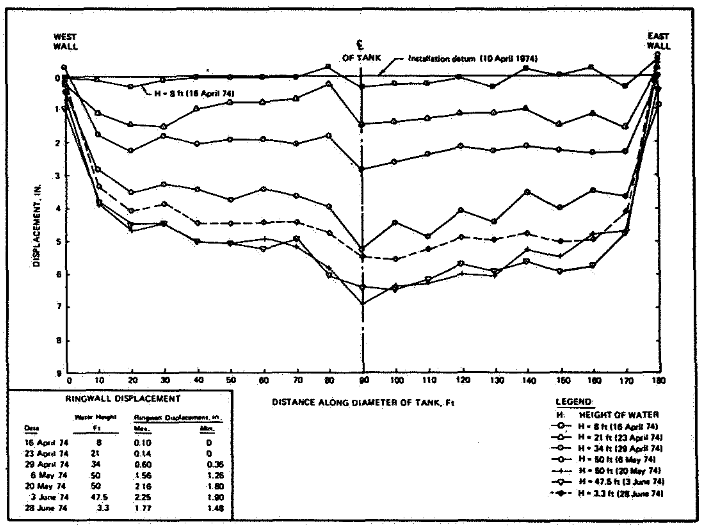
Subsurface conditions at Greenwood were explored by means of ten borings. The moderately compressible deposit at the site consists of about 20 ft. of loess (brown silty clay) overlying about 25 to 30 ft. of glacial drift (brown silty or sandy clay). The sand deposit below the glacial drift can be considered slightly compressible in relation to the deposits of loess and glacial drift. The undrained shear strength of the loess and glacial drift was found to be essentially greater than 1,000 lb./sq.ft. The undrained strength was evaluated by means of unconfined compression tests and unconsolidated-undrained triaxial compression tests. Groundwater was typically found at a depth of about 45 ft.

The water test was made by filling the tank with 50 ft. of water. This water height was maintained for a period of 18 days. The height of water was then reduced to 47.5 ft. for the air pressure test, after which the water was pumped out. The measurements of displacements of the base plate were made using the double fluid settlement device throughout the period of the water test. These measured displacements are shown in Figure 4. The displacements of the ring wall were measured with an optical level and the minimum and maximum measured displacements are tabulated in Figure 4. The total displacement of any point within the tank is the sum of the ring wall displacement and the double fluid settlement device displacements.

Under the maximum water load of 50 ft. a measured displacement of 4.7 in. was found to occur at a distance of 10 ft. from the wall of the tank, resulting in an angular rotation of about 1/26 in the vicinity of the wall. The maximum measured displacement of the center of the tank, relative to the ring wall, was about 6.9 in., resulting in a maximum angular rotation of about 1/157 between the ring wall and the center of the tank. During the water test, the minimum and maximum measured displacements of the ring wall were found to be 1.9 in. and 2.3 in. The out-of-plane tilt of the ring wall is calculated to be about 1/4 in. in an arc length of 30 ft.

Near the end of the water test, when about 3.3 ft. of water remained in the tank, the double tube settlement device data indicated that a rebound of 1.4 in. had occurred at the center of the tank and a rebound of 0.6 in. had occurred at a distance of 10 ft. from the wall. With about 6 in. of water remaining in the tank, the ring wall rebounded a maximum of 0.6 in.

After completion of the water test, direct measurements of the final position of the base plate were made from an internal water level as was done at Garner and Mankato. The measured and inferred displacements are shown in Figure 5. A displacement of 3-1/4 in. (3-1/2 in. inferred displacement) was found to occur at a distance of 2 ft. from the wall of the tank, resulting in an angular rotation of 1/7 in the vicinity of the wall. A comparison of the final



RINGWALL DISPLACEMENT

Date	Water Height Ft	Ringwall Displacement, in. Max.	Min.
16 April 74	8	0.10	0
23 April 74	21	0.14	0
29 April 74	34	0.60	0.36
6 May 74	50	1.56	1.26
20 May 74	50	2.16	1.80
3 June 74	47.5	2.25	1.90
28 June 74	3.3	1.77	1.48

Figure 4. Measured displacement of tank bottom during water test, ammonia storage tank, Greenwood, Nebr.

Table 2. Summary of experience data on rotations of base plates adjacent to ring walls

Tank type and location	Size dia.(ft.)	Size ht.(ft.)	Measured* rotation adjacent to ring wall	Inferred rotation adjacent to ring wall	References
Ammonia Storage Tank, Garner, Iowa	170	62	1/9	—	
Ammonia Storage Tank, Greenwood, Nebraska	180	56	1/7	—	
Ammonia Storage Tank, Mankato, Minnesota	170	62	1/10	—	
Oil Storage Tank, River Tees, England Tank No. 2101-FD	186	54	—	1/42	Penman and Watson, 1967 (*1*)
Oil Storage Tank, River Tees, England Tank No. N3000-F	128	54	—	1/16	Penman and Watson, 1967 (*1*)
Oil Storage Tank, River Tees, England Tank No. 2402-F	45	48	—	1/5	Penman and Watson, 1965 (*2*) and 1967 (*1*)
Oil Storage Tank, River Tees, England Tank No. T-40	64	30	—	1/12	Penman and Watson, 1963 (*3*)
Oil Storage Tank, European Location	185		—	1/7**	Clarke, 1971 (*4*)

* Rotation given as vertical/horizontal from direct measurement data after water test.
** Failure of tank.

deflected shape determined from the double tube settlement device and the other readings is shown in Figure 6. The close agreement in the measurements in the vicinity of the ring wall is apparent.

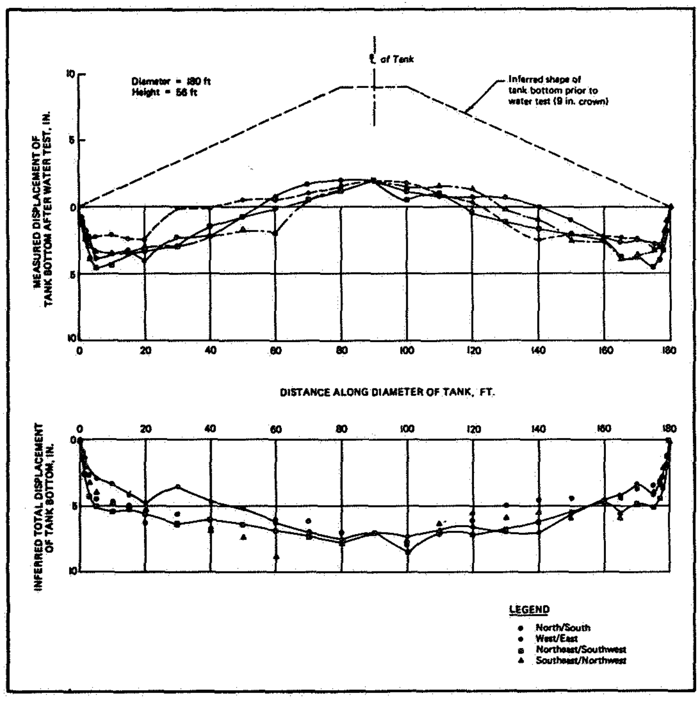


Figure 5. Measured and inferred displacement of tank bottom after water test, ammonia storage tank, Greenwood, Nebr.

Data are compared

Measurements of base plate displacements of two atmospheric tanks have been found in the literature and are shown on the left in Figure 7. The displacements are plotted as a percentage of the center displacement. For comparison, the data on base plate displacements at the end of water testing for the three ammonia storage tanks are shown at the right in Figure 7.

Displacement measurements for the ammonia storage tanks were obtained at many more points than the measurements for the atmospheric tanks. Consequently, the distor-

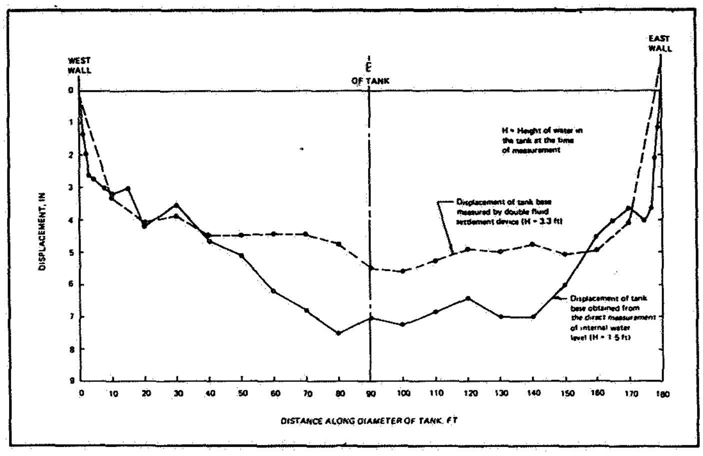


Figure 6. Comparison of tank base displacement measured by double fluid settlement device and direct measurement of internal water level, storage tank, Greenwood, Nebr.

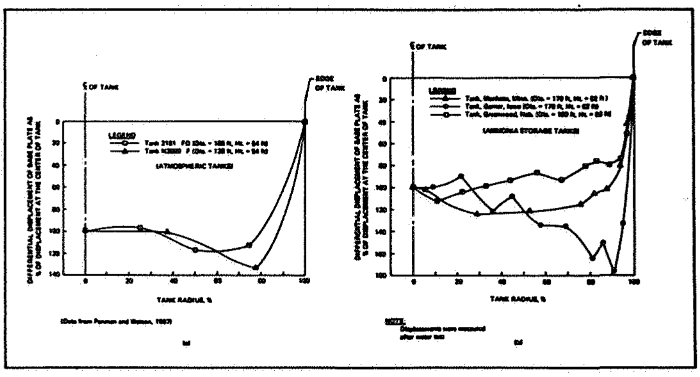


Figure 7. Plot of differential displacements of base plate as a percentage of the center displacement vs. radius of tank in percentage.

tions of the former appear more severe than the distortions of the atmospheric tanks where smooth curves were drawn through a limited number of points. It is apparent from Figure 7 that 60 to 100% of the center deflections of the base plates occur within a distance of about 10% of the tank radius from the edge.

This conclusion is confirmed by additional data from the literature, not shown in Figure 7 because insufficient measurements were obtained beneath those tanks. Displacement measurements were obtained on, and adjacent to, the edges of two tanks in England and suggest very substantial rotations of the base plates adjacent to the edge. A summary of observed and inferred base plate rotations adjacent to the edges for a number of tanks is presented in Table 2. The data for oil storage (atmospheric) tanks included in this table are for tanks constructed on compacted fill pads, without ring walls.

Only one tank failure is reported by Clarke (1971) (*4*), and it was associated with an angular rotation of about 1/7. This tank had been mud-jacked after the first water test. The jacking introduced angular distortions at the ring wall which changed in direction from about 1/7 directed upward in about the first 7 ft. to about 1/8 directed downward in about the next 5 ft.; i.e., at about 7 ft. from the ring wall, the base plate rotated through an angle of about 165° with an apparent large curvature. Failure occurred during a second water test.

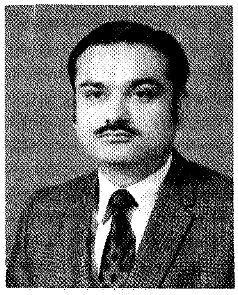
Discussion and conclusions

It appears reasonably well-documented that major displacements of base plates occur within a few feet of the edge of many tanks. These displacements are not predictable using the generally accepted Boussinesq stress distribution which assumes a homogeneous, isotropic material with a constant modulus of elasticity. Gibson, in a series of papers, has shown that the observed displacements may be predicted if non-uniform material properties are assumed. (*5,6,7*) For this situation, the stress distribution is dependent on the soil elastic constants. The settlement may then be computed from a knowledge of the soil compressibility. Considerable success in predicting the observed displacements of a tank founded on a hard chalk was reported by Burland et al. (1973) (*8*) using a finite element analysis and the Gibson solution for determining the stresses.

It is our opinion that users of tanks would be well-served if additional performance data were made available. These data could then be analyzed to validate prediction techniques and could form the basis for realistic assessment of the tolerable displacements of tanks. The available data suggest that, too often, tanks are founded on expensive pile foundations because the tolerable displacements are unknown and the available settlement prediction techniques have not been shown to be sufficiently reliable. #

Literature cited

1. Penman, A.D.M., and Watson, G.H., "Foundations for Storage Tanks on Reclaimed Land at Teesmouth," *Proc. Inst. of Civil Engineers,* (1967), pp. 19-42, London.
2. Penman, A.D.M., and Watson, G.H., "The Improvement of a Tank Foundation by the Weight of Its Own Test Load," *Proc. Sixth Int. Conf. on Soil Mechanics and Foundation Engineering,* 2, 168-173 (1965), Montreal, Canada.
3. Penman, A.D.M., and Watson, G.H., "Settlement Observations on an Oil Tank," *Proc. European Conf. on Soil Mechanics and Foundation Engrg.,* **1**, 163-171 (1963), Wiesbaden, West Germany.
4. Clarke, J.S., *Oil & Gas J.,* **70**, 83 (July 5, 1971).
5. Gibson, R.E., *Geotechnique,* **17**, 58-87 (1967).
6. Gibson, R.E., and Sills, G.C., "Some Results Concerning the Plane Deformation of a Non-Homogeneous Elastic Half-Space," *Proc. of Roscoe Memorial Symposium,* Cambridge, University, pp. 564-572 (1971).
7. Brown, P.Y., and Gibson, R.E., *Canadian Geotechnical J.,* **9**, 467 (1972).
8. Burland, J.B., Sills, G.C., and Gibson, R.E., "A Field and Theoretical Study of the Influence of Non-Homogeneity on Settlement," *Proc. 8th International Conf. on Soil Mechanics and Foundation Engineering,* Vol 1., Part 3, 39-36 (1973), Moscow, Russia.



AHMAD, S.

ESRIG, M. I.

DISCUSSION

LES SUTHERLAND, CF Industries: Can you explain to me the difference in criteria for the different allowable amounts of settlement quoted by Esso Research? Class one, two, and three?

ESRIG: Yes, the different criteria are associated with combating edge distortions. Esso found that when large settlements occurred, large edge distortions also occurred. They minimized the effect of the edge distortions by widening the annular base plate. Thus, for Class I, where the settlements were 6 in. to 1 ft., a 6 ft. wide plate was recommended. Class II required a 4 ft. wide plate and Class I, a 2 ft. wide plate. They determined by experience that they needed these different classes. I am told, however, that they are now modifying these criteria.

SUTHERLAND: In thinking back, last year Clay Hill presented a paper on ammonia storage tank problems and one of the primary problems the industry has been experiencing is problems with under tank heating. And breakage of electric coils, ruptures of glycol heating systems and such. And I think these settlements might possibly explain part of those problems.

ESRIG: That is right. A tank was lost recently in Illinois by frost heave, and, although I have no detailed information, I suspect that it could be the result of cutting of the under tank heating coils.

Q. Are there elastic deformations in these foundations as well as the permanent deformation you're able to measure after the tanks are out?

ESRIG: Yes. I did not point that out to you. In the continuous-reading data of displacement at Greenwood vs. distance along the diameter of the tank, there was a red curve in the slide that showed the heave (rebound) on unloading. The tank rebounded about 1-1/2 in. This is essentially elastic deformation that occurred when the water test load was removed. Under product loads, we would expect that the center of the tank is going to "breathe" about 1 in. The ringwall, as I recall, rebounded about 1/2 in. when the water test load was removed. Under elastic conditions, it appears that about half the center settlement will occur at the edge.

Thus, we are certain that there are elastic displacements and that tanks do "breathe." We have been very concerned with these displacements under operating conditions for a variety of tanks. Recently, I was asked by Kellogg to make some predictions for several LNG tanks of the movement expected during operation. I predicted 1 in. at the ringwall but also told them I could not be certain of the accuracy of these predictions. The maximum displacement at the ringwall, I estimated as 2 in. I was told that they put enough flexibility in the connections to take care of the maximum predicted settlement.

BILL STAMPE, St. Paul Ammonia Products: I'd like to share with you a little bit of my own experiences in a former business establishment that I worked for. It's a consulting engineering firm in Dubuque. We have an unusual soil condition in most of the industrial area that's along the river in that there's an eight to ten foot thick mud layer that underlies most of the sand down by the Mississippi river.

In order to erect large tanks and warehouses and other buildings that would exert a significant load on the ground, we found rather than going to pile driving to support these things that we superimposed a load of earth on top of the ground that was equal to one and a half times the soil loading that would be experienced by either the warehouse or the tank.

Soil is probably two and a half times the density of ammonia, so roughly a 20 or 25 foot fill of dirt would represent the tallest ammonia tank that would be built today. Settlement plates that are placed on the original ground will record how far the fill will force the ground down. In our area it would go down as much as six or seven feet.

In starting the fill we would bring up the first few feet to what would probably be the top of the ring wall after settlement and compact it to 100 percent proctor density. The balance of the fill was not compacted and it was merely raised, say, 25 feet in the air with a conventional cat and scraper. After filling, measure these settlement plates and plot settlement versus time. It might take several months before settling ceases.

Then the cat and scrapers remove the fill back down to the ringwall elevation, excavate for the footings, back fill and make sure you're 100% proctor inside the footings. To my knowledge there have been no problems whatsoever with any of the buildings or the tanks that were put up that way in our area.

There are no anhydrous ammonia tanks put in that way in Dubuque but I offer as a possible suggestion that if this is a severe problem with the industry, dirt is pretty cheap to move.

ESRIG: By and large time is not. We have used preloading for the Columbia Gas LNG tanks in Cove Point, Maryland where we had questions about the in-service displacements. It has also been done in a large number of other places. Preloading is a good technique where it is appropriate in terms of time. However, we have found that where displacements during preloading are large, in-service displacements may be too large for the long term behavior of the tank.