Behavior of Grain Elevator Foundations Subjected to Cyclic Loading

Comportement des fondations de silos à grains soumises à des chargements périodiques

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Summary

Two reinforced concrete grain elevators on raft foundations exert net soil pressures cyclically of 1·0 to 5·0 kips per sq.ft. Two distinctly different soil deposits, namely coastal plain and alluvial, are involved.

Load and settlement data are available for a period of five years after construction. In both cases, the average settlement is about 10 in. The settlements in general take place with only a slight time-lag. Elastic rebounds up to 7/8 in. are observed with each unloading cycle. Differential settlements up to 6 1/4 in. accompanied by severe distortions of the rafts are noted.

Observations on the superstructures as well as the raft foundations lead to the conclusion that such structures are rather flexible and are capable of considerable distortion without impairing their usefulness.

Sommaire

Deux silos à grains, en beton armé, avec des fondations sur radier, exercent des pressions sur le sol variant périodiquement de 1·0 à 5·0 kip par pied carré. Ils sont assis sur deux natures de terrains, l'une de plaine côtière et l'autre alluviale.

On dispose de mesures de la charge et du tassement pour une période de cinq ans après la construction. Dans les deux cas, le tassement moyen est d'ordre de 10 in. En général, le tassement se produit avec peu de retard. Des gonflements élastiques allant jusqu'à 7/8 in. sont observés à chaque cycle de décharge. On note également des tassements différentiels jusqu'à 6 1/4 in. accompagnés de déformations importantes du radier.

L'observation des superstructures et des radiers montre que les ouvrages de ce type sont assez souples et capables de supporter des déformations considérables sans réduire leur possibilité d'utilisation.

Introduction

Settlement observations have been obtained on two large grain elevators which were constructed within the past seven years in widely separated areas in the United States. Not withstanding the great differences in subsoil conditions at the two sites, the structures have exhibited strikingly similar settlement patterns. Because these structures are typical of existing grain elevators and the many new ones currently being built, it is felt that a description of their behavior under seasonal or cyclic loading is of general interest.

In the following paragraphs the two structures are discussed separately. For each site the subsoil conditions, type of structure, loads, settlement pattern, and overall behavior of the structure are discussed.

Wilson, North Carolina site

Description of Structure—The grain elevator is a reinforced concrete structure consisting of fourteen circular bins of 18-ft. inside diameter arranged in two rows of seven each. The bins have 6-in. thick walls and rest on a raft foundation 137 ft. long, 50 ft. wide, and 26 in. thick. The top of the raft is flush with the ground surface. The walls of the bins bear directly on the raft. No dowel bars or other reinforcement exist across the joint. The edge of the raft is scalloped or indented (Fig. 1) and the raft is cantilevered 4 ft. beyond the bin walls on the sides and 2 ft. on the ends.

The bins are tangent to each other and tied together structurally in the longitudinal direction. In a transverse direction the two rows of bins are connected at each bin by cross walls 4 ft. long forming interstice bins. The bins are 125 ft. high. A head-house extends an additional 35 ft. in height above four of the bins at one end of the structure. The total storage capacity is 401,000 bushels.

An 8-ft. high conveyor tunnel enters beneath the raft near one end of the structure. The bins terminate in conical hopper bottoms approximately 6 ft. above the raft. The bin loads are transferred to the raft by means of short reinforced concrete columns which support the bin bottoms and by the bin walls which transmit part of the grain load by friction. This arrangement allows ready access to the top of the raft for settlement observations.

Subsoil Conditions—The Sunderland formation of early Pleistocene age extends from the surface to an average depth of 20 ft. The sediments are marine in origin having been deposited as shallow sea sediments when the sea was at a higher stand during an interglacial age. The formation is comprised of a rather heterogeneous mixture of red, tan, and gray variegated sands silts, and clays. In general, the upper 10 ft. of soil (Fig. 1) is cohesive consisting of poorly stratified medium to stiff sandy clay and clayey sand with occasional sand and silt lenses. The lower 10 ft. of the Sunderland formation is of looser or softer nature and is comprised of laminated fine silty sand, silt, and clayey silt. Average soil properties are given in Table 1.

At a depth of 20 ft. (Fig. 1) the Sunderland formation rests unconformably upon a fairly thick layer of soft to medium gray silty clay of marine origin. This layer extends between the average depths of 20 ft. and 44 ft. and represents the Yorktown formation of Late Miocene age. The clay is highly compressible as indicated by average values of natural void ratio of 1.4 and compression index of 0·65. The Casagrande construction shows a preload of only 1·0 tons per

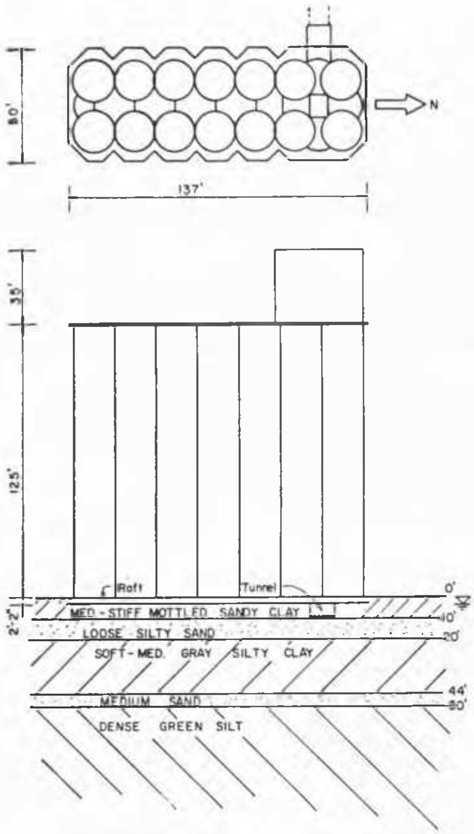

Fig. 1 Plan and profile showing average subsoil conditions. Wilson, North Carolina.

Plan et coupe montrant les caractéristiques moyennes du sol. Wilson, North Carolina.

sq. ft. in excess of the overburden pressure. The coefficient of permeability as computed from the consolidation tests averages 1×10^{-7} cm per sec. Very thin laminae or partings of fine sand occur in the sandy clay which would tend to increase the rate of consolidation in the field. Additional soil properties are given in Table 1.

Table 1
Wilson, North Carolina

Depth, Ft.	*N*	$q^*_{u/2}$, lbs. per sq. ft.	*LL*	*PL*	*w*
0-10	15	300-3500	42	19	22
10-20	6	400-800	45	23	27-44
20-44	3-4	500-1000	55	25	50
44-50	12				
50-100	120				

* q_u - unconfined compressive strength.

The gray clay is underlain by a zone of sand and silty sand of loose to medium density which average 6 ft. in thickness (Fig. 1). The sand in turn is underlain by a thick layer of very hard and compact dense green silt (glauconite). Both of the above strata are considered to represent the lower part of the Yorktown formation.

The water table is at a depth ranging from 5 ft. to 10 ft. below the surface depending upon the seasonal rainfall.

Load-Settlement Relationships—The net dead load due to the weight of the structure is 1·84 kips per sq. ft. This value is somewhat higher than normally encountered for similar structures since the raft is founded just 2 ft. below the ground surface. The average net load increases to 4·80 kips per sq. ft. when the bins are loaded with grain. The loading season extends from December through May. During the other 6 months the live load is less than 1 kip per sq. ft. The variation of the net load with time is shown in Fig. 2. The cyclic

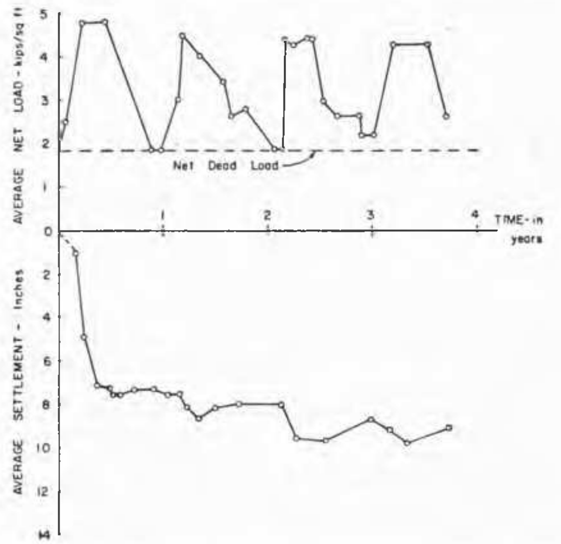

Fig. 2 Load-settlement-time relationships. Wilson, North Carolina.

Relations de charge-tassement-temps. Wilson, North Carolina.

nature of the loading is obvious. The grain elevator has never been completely loaded. Under various conditions of loading, the total net load under large portions of the raft has exceeded the average by 0·70 kips per sq. ft.

The average settlement of eight observation points on the raft is also plotted against time in Fig. 2. About 7 in. of the 9·8 in· total settlement took place during the first 4 months of the first load cycle. Maximum and minimum settlements are approximately 2·7 in. more, and 3·6 in. less, respectively, than the average settlement.

A slight increase in settlement with time is noticed while the load remains essentially constant. Rebounds of from 3/8 in. to 7/8 in. result upon decrease of the live load (Figs. 2 and 3). Reapplication of the live load produces a slight increase in settlement over the settlement corresponding yo the same load in the previous cycle. This effect amounts to about 3/8 in. at the maximum loads. There is some indication that the cyclic effect decreases with increasing number of cycles (Fig. 3).

The major part of the settlement may be accounted for by consolidation of the subsoil and by immediate elastic strains following application of the load. However, the factor of safety with respect to a bearing capacity failure was estimated to have been only slightly greater than unity during the first loading season. It is probable that some of the early settlement may be attributed to inelastic shearing distortions of the highly stressed subsoil. Additional inelastic settlements have been induced by the cyclic loading. This effect is in accordance with laboratory experience on cyclic loading of soils.

Behavior of Structure—The pattern of settlement is indicated by the contours shown in Fig. 4a. Although the differential settlement is 6·3 in., much of it is in the form of tilting

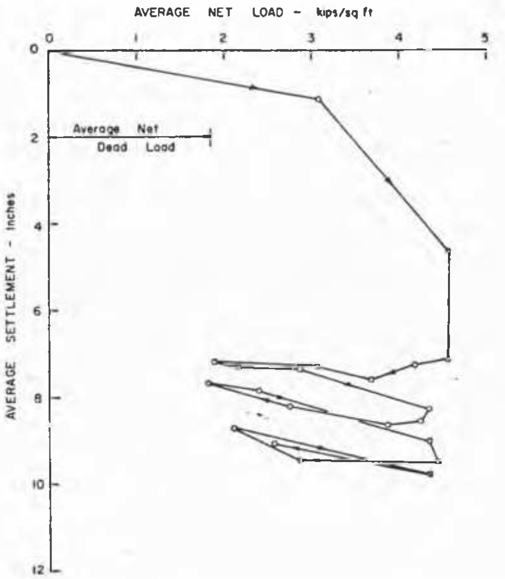

Fig. 3 Cyclic load-settlement curve. Wilson, North Carolina.
Courbe de charge-tassement périodique. Wilson, North Carolina.

toward the end which has been the more heavily loaded. There is also a slight trough of settlement with the interior of the raft having settled from zero to 1 in. more than the edges. In addition, there is some local warping near the corner where the conveyor tunnel enters beneath the raft. This northwest corner has settled the least because it has always been more lightly loaded and it has been held up to a certain extent by the tunnel.

The raft as a single structural member is relatively flexible on account of its large area with respect to its thickness. However, when considered in conjunction with the superstructure and its contents, the unit as a whole behaves as though it were more rigid. Although there is no structural continuity between the raft and bin walls, there has been no visible separation or horizontal movement at the junction.

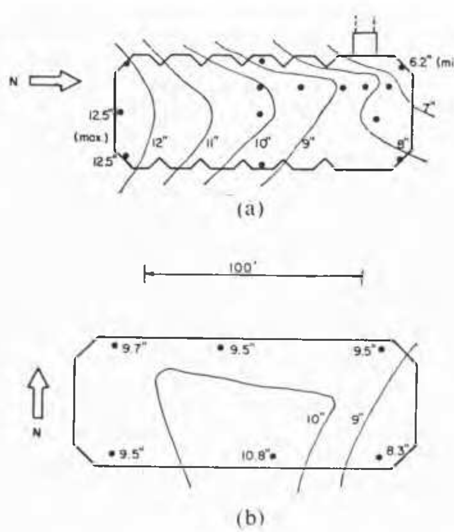

Fig. 4 Plan showing settlement contours. a) Wilson, North Carolina. b) Topeka, Kansas.
Plan montrant les lignes d'égal tassement. a) Wilson, North Carolina. b) Topeka, Kansas.

Rigid behavior of the unit is indicated by the settlement pattern. Assuming complete flexibility and a Boussinesq distribution of stress, the settlement due to the deep-seated consolidation theoretically should have been 18 in. at the center and 5 in. at the edges. Since a bowl-like settlement pattern developed to only a very limited extent, it is necessary to assume that the rigidity of the superstructure resulted in a redistribution of stress in which the pressure beneath the center of the raft was decreased and that beneath the edges increased. The edges of the raft have punched into the soil leaving vertical scarps 6 in. high which would bear out the supposition of high edge pressures.

Flexibility is present in the raft and superstructure, however, as pointed out by the small trough-like settlement along the centerline and the local warping in the vicinity of the conveyor tunnel. In addition, vertical movements of as much as 3/8 in. have been noted at the corner of the raft upon the loading or unloading of a single adjacent bin. The movement takes place in a matter of hours and observation points at a greater distance are not affected.

Of importance is the response of the structure to the differential settlements. Unsatisfactory behavior occurred in at least four different aspects which necessitated maintenance although the structural integrity was not immediately impaired. The concrete lining of the tunnel, which entered beneath the raft, cracked badly and eventually sheared off directly beneath the raft edge. A total vertical displacement of 6 in. was noted in the lining at that point. Th: raft suffered only one crack that could be discerned. Te crack was located beneath the outer bin wall in the vicinity of the tunnel and extended out through the cantilevered edge. The crack formed in an area of local warping.

The most troublesome cracks are those that developed in the bin walls at about midheight in the area of local warping near the conveyor tunnel. Most of the cracks are horizontal and appear to follow planes of weakness caused by cold joints formed during of the concrete. Two long vertical cracks are also present and they follow the position of vertical jacking rods. The cracks open or close depending upon the distribution of load in the bins. Repeated opening and closing of the cracks has resulted in spalling of the concrete adjacent to the cracks.

The fourth series of cracks formed in some of the columns supporting the bin bottoms. The cracks are horizontal and open upon unloading of the bins. Under load, the cracks become nearly invisible. The cause of the cracking appears to be a stress relief phenomenon and is associated with creep of the concrete under sustained load. Such behavior is entirely a structural phenomenon and should not be associated with the settlement of the structure.

Topeka, Kansas, site

Description of Structure—The grain elevator is a reinforced concrete structure consisting of twelve circular bins of 24-ft. inside diameter arranged in two rows of six each. The bins have 7-in. thick walls and rest on a raft foundation approximately 157 ft. long, 59 ft. wide, and 28 in. thick. The top of the raft is 3 ft. 2 in. below the ground surface. The walls of the bins bear directly on the raft with no dowel connections. The raft is cantilevered 4 ft. 6 in. beyond the bin walls.

The bin walls are tangent to each other in both longitudinal and transverse directions and are tied together structurally (Fig. 5). The star shaped interstices thus formed are also used as bins. The bins are 120 ft. high and the total capacity is 665,000 bushels.

A tunnel approximately 8 ft. wide by 7 ft. 6 in. deep extends beneath the bins on the longitudinal center-line of the structure. The bin loads are transmitted directly to the raft except for that portion which is transmitted by friction to the bin walls and thence to the raft.

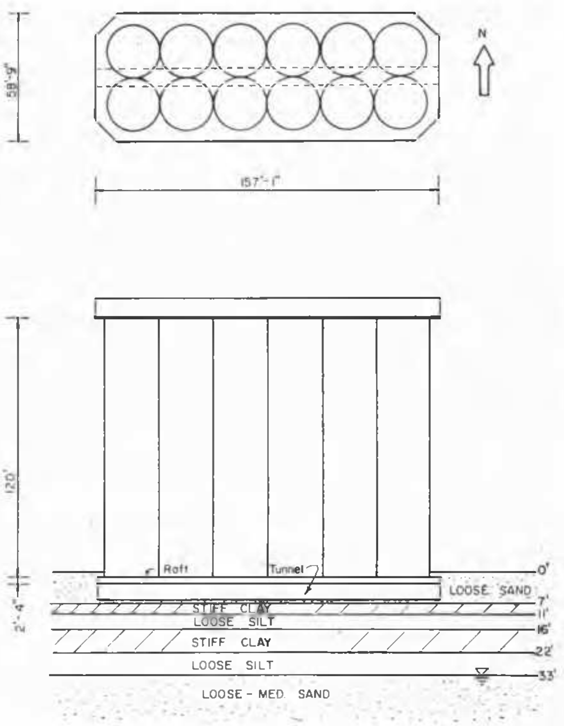

Fig. 5 Plan and profile showing average subsoil conditions. Topeka, Kansas.

Plan et coupe montrant les caractéristiques moyennes du sol. Topeka, Kansas.

Subsoil Conditions—The site is located on an alluvial terrace of the Kansas River about 20 ft. above the present flood plain. The ground water level is at an average depth of 33 ft. but is subject to seasonal variations of several feet. The subsoil consists of alternating zones of loose sandy silts and stiff jointed clays, each zone ranging from 4 ft. to 10 ft. or more in thickness. The generalized soil profile is shown in Fig. 5 and the average soil properties are given in Table 2.

Table 2
Topeka, Kansas

Depth, Ft.	*N*	*Vane Shear Strength* lbs. per sq. ft.	*LL*	*PL*	*w*
0-7	2-11	1000-2000			
7-11	6-12	> 2500	43	22	25
11-16	6-11	1800-3200			
16-225	6-18	> 3200	55	24	26
22-33	5	2300	27-45	22	24-37

Somewhat lower strengths were obtained along the south side of the structure as compared with those along the north side. This trend was apparent only in the two upper soil units.

The soil occurring between the average depths of 22 ft. and 33 ft. is the weakest, the thickest, and the most variable of the zones described. It consists of soft to medium silt ranging from clayey and plastic to sandy and cohesionless. The following values were determined from consolidation tests : natural unit weight 104-107 lbs. per cu. ft., void radio 1·08-1·10, compression index 0·31-0·38, and preload in excess of present overburden pressure 0-200 lbs. per sq. ft. Similar values were determined for the other silt layers. The stiff clays on the other hand show preloads on the order of 3 000 lbs. per sq. ft.

Below a depth of 33 ft. the site is underlain by a thick layer of fine to medium sand of loose to medium density. Limestone bedrock is encountered at an approximate depth of 80 ft.

Load-Settlement Relationships—The average net load soil pressure on the raft is 1·08 kips per sq. ft. With the first seasons grain loading the average net soil pressure increased to 3·3 kips per sq. ft. and with subsequent loadings reached a maximum of 4·33 kips per sq. ft. The north side of the structure has always been loaded more heavily than the south side to compensate for southward tilting, and the net soil pressure on the raft in the north half is maintained at about 1·0 kips per sq. ft. higher than for the south half. The cyclic nature of the loading is indicated on Fig. 6 where the average

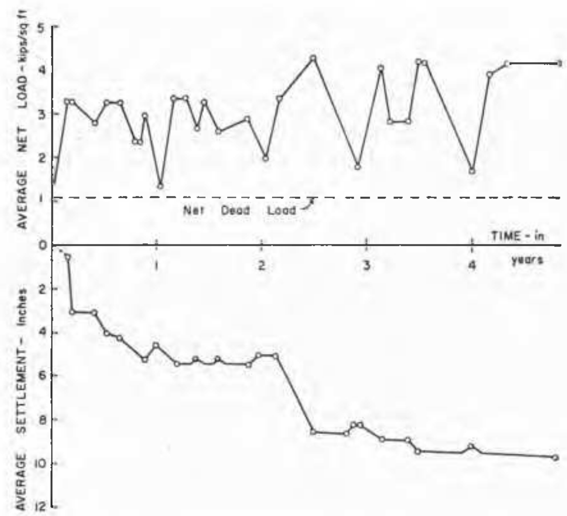

Fig. 6 Load-settlement-time relationship. Topeka, Kansas.

Relations de charge-tassement-temps. Topeka, Kansas.

net load is plotted against time. The loading season begins in May and the loads remain high, although there is considerable oscillation, for about 8 months. The loads then gradually decrease and a minimum pressure of about 1.5 kips per sq. ft. is exerted over a period of about 2 months.

The average settlement of six observation points located near the base of the outer bin walls is also plotted against time in Fig. 6. It will be noted that about 5.5 in. of the total average settlement to date of 9·5 in. took place during the first loading season and that half of that was obtained in two month's time. During this cycle there was a continued settlement with time at fairly constant load. However, the later loading cycles showed negligible time-lag.

The effect of cyclic loading upon the settlement is shown in Fig. 7 where the average net load is plotted against the average settlement. It is noted that a reapplication of load in excess of that of previous cycles resulted in additional settlements of from 1 in. to 3 in. depending upon the magnitude of the added load. During the unloading cycle there is an elastic rebound amounting from 1/4 in. to 3/4 in. Upon reapplication of load there is a slight increase in settlement over the settlement corresponding to the same load in previous cycles by amounts of 1/4 in. to 1/2 in. The data indicate that this effect is less pronounced in the last cycle of loading.

A major part of the early settlement may be accounted for by elastic compression and compaction in the upper sand and silt layers. Although a factor of safety against a bearing capacity failure of 2·0 to 2·5 was estimated for the structure

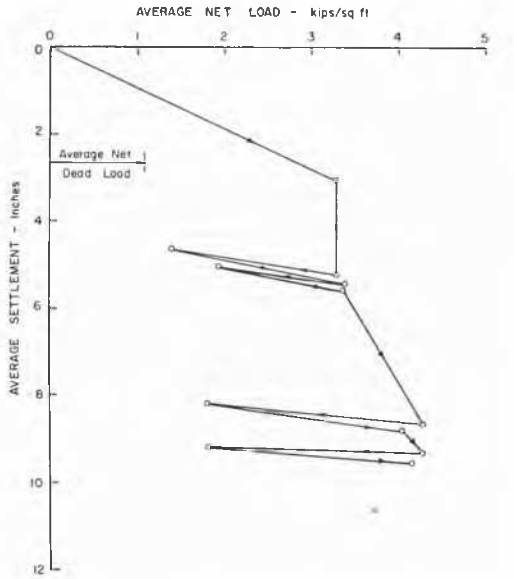

Fig. 7 Cyclic load settlement curve. Topeka, Kansas.
Courbe de charge-tassement périodique. Topeka, Kansas.

as a whole, some localized failure probably took place in the upper silty sand layer. Thus a shearing distortion or punching in the upper sand layer contributed to the early settlement. The two clay layers are preloaded and relatively negligible settlements may be attributed to them. The lower silt layer is saturated by capillarity and consolidation of this layer is the probable cause of any-time-lag in the settlements. Additional settlements due to cyclic loading, including an observed decrease in the cyclic movement, are in accord with laboratory experience on the cyclic loading of soils.

Behavior of Structure—The pattern of settlement is shown by the contours in Fig. 4b. The maximum differential settlement is 2·5 in. and it takes place over a distance of only 48 ft. There is no tilting of the structure and it has settled as a unit with the exception of the center of the south side where there is a sharp bowl of subsidence opening to the south. The exact pattern is not known since there are no observation points inside the structure. The greater settlement of this part of the raft cannot be caused by unequal loading since the load on the south half of the raft is about 1·0 kips per sq. ft. less than at the north half in order to compensate for the early tendency of the structure to tilt southward.

The differential settlement can only be accounted for by variations in the subsoil. The boring and testing program did indicate erratic subsoil conditions and somewhat weaker soils along the south side of the structure. During the first loading cycle when the raft was loaded uniformly throughout, the south side settled an average of 1 in. to 1·5 in. more than the north side. The exception to this is at the southeast corner where minimum settlements have always been obtained (Fig. 4 b).

The settlement pattern again indicates that the raft foundation and superstructure taken as a unit behave as though they comprised a rigid structure insofar as total settlement and tilting is concerned. However, sufficient flexibility is present to allow local settlement and warping of 2 in. or so in response to variations in loading and subsoil conditions. It should be noted that the edges of the raft rest on six feet more of compressible material than the center of the raft which helps to reduce any tendency for a bowl shaped settlement problem.

No cracks have been found in any part of the superstructure or main raft. A few small vertical cracks have developed in the tunnel walls and floor opposite the bin unloading spouts but they are not considered of consequence. Settlement of the adjacent headhouse structure and of the grain elevator caused the two structures to lean toward each other. This movement crushed a connecting catwalk and also resulted in the roof of the grain elevator being pushed 2 in. eastward. The roof beams were pushed off their supports and a new roof supporting system had to be installed.

Conclusions

Rigidity of structure—Although the raft and superstructure are by themselves relatively flexible structural members, their behavior as a unit in combination with the material stored in the bins appears to be that of a moderately rigid structure. Any tendency for the raft to develop a bowl-like settlement due to deep seated consolidation, as would be predicted for a uniformly loaded structure in accordance with a Boussinesq stress distribution, is accompanied by a transfer of load to the outer portions of the raft. The dead load of the bin walls-and the live load transferred by friction to the walls-is thus redistributed by whatever rigidity the superstructure possesses. Rigid behavior of the structures is evidenced by the absence of pronounced bowls of settlement, by tilting as a unit in both the longitudinal and transverse directions, and possibly by the edge punching effect. The latter would indicate high contact soil pressures beneath the raft edges. The erratic nature of the soil profiles at both sites precludes any definitive treatment of the contact pressures.

On the other hand, the unit is sufficiently flexible to allow local warping to take place in response to unequal loading and variations in the subsoil. Settlement observations indicate that the magnitude of the local warping may be on the order of 2·5 in. and take place within short distances. Some flexibility is also indicated by the development of a small trough-like settlement pattern at the Wilson site. The flexibility of the superstructure is provided in part by change in shape of the circular bins. Strains imparted by local warping may be sufficiently severe to cause cracking of the bin walls as was noted for the Wilson structure.

Cyclic loading effects—An immediate elastic rebound of about 1/4 in. to 1 in. occurs during each unloading cycle. Upon reapplication of load the rebound immediately reappears as settlement plus an additional amount of inelastic settlement of about 1/4 in. to 1/2 in. This cyclic effect decreases with increased number of loading cycles. It is estimated that the total settlement at each for sites in from 1 in. to 2 in. greater because the load was cyclic rather than static.

Design recommendations—The settlement patterns observed for the two structures provide sufficient evidence to recommend that reinforcement be placed in two directions in both faces of the raft. Where large settlements are anticipated, conveyor tunnels entering beneath the raft should either be eliminated or designed for large vertical movements at the raft edge. In addition, where local warping may be caused by unequal loading or variations in subsoil conditions, an increased thickness of raft would provide added rigidity which would decrease the deformation of the bin walls and the likelihood of cracking. The base of raft foundations should, in general, be placed at least six feet below the ground surface to help prevent the edge punching effect. Sufficient clearance, or provision for adjustments, should be allowed between adjacent structures to avoid problems induced by tilting.