Construction Load Effects on Settlement of a Soft Clay Foundation

Effets de la charge de construction sur le tassement d'une fondation sur l'argile molle

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SUMMARY

A pumping plant located in an area of deep, soft lake sediments on the Bureau of Reclamation's Willard Canal near Ogden, Utah, required a friction pile foundation. The specified bottom elevation of the plant was 35 feet below the surface in soft sediments of poor stability, resulting in an extensive excavation area which was later backfilled. Observation of foundation settlement was started immediately after piles were placed. Settlement which occurred during construction was of much concern. Appreciable load changes caused by backfilling the extensive excavation as construction progressed were distinctly related to this settlement. Their effects were apparently so extensive that they encompassed the whole pile foundation. After backfilling, the plant appears to be satisfactorily supported by the friction piles as expected. However, these settlement records demonstrate the importance of considering excavation and backfilling load changes.

SOMMAIRE

Une usine de pompage située dans une région de sédiments lacustres profonds et mous sur le Canal Willard du Bureau de Réclamation près d'Ogden, Utah, demanda une fondation de pieux à friction. L'élévation spécifiée du fond de l'usine fut 35 pieds au-dessous de la surface dans les sédiments mous de faible stabilité, résultant en une surface d'excavation très vaste qui à été remblayée plus tard. Les observations du tassement de la fondation furent tout de suite commencées après que les pieux furent placés. Le tassement qui eut lieu pendant la construction fut de grand intérêt. Les changements appréciables de charge causés par le remblayage de l'excavation à mesure que la construction progressait furent nettement en relation avec le tassement. Leurs effets furent apparemment si importants qu'ils ont influencé toute la surface de la fondation. Après le remblayage, l'usine semble être soutenue d'une manière satisfaisante par les pieux à friction comme espéré. Néanmoins ces enregistrements de tassements démontrent l'importance de considérer les variations de la charge dues à l'excavation et au remblayage.

THE SELECTION OF THE SITE for the Willard Pumping Plant on the Bureau of Reclamation's Weber Basin Project near Ogden, Utah, was a considerable problem in exploration and required extensive investigations of deep, soft lake sediments. The plant is adjacent to the project's major feature, the 14.5-mile-long Willard Dam, which encloses a portion of Willard Bay on Great Salt Lake. The dam stores fresh water which is pumped by the Willard Pumping Plant into a distribution system near Ogden. The pumping plant site, Fig. 1, necessarily was located in the broad expanses on the flat shores of the Bay area, which had no promise of an adequate near-surface foundation and required piles. The principal problem of the exploration programme was to obtain a site for the structure which would have firm material within a reasonable depth, consisting of dense deposits of either sediments or sand.

The example log in Fig. 2 shows extremely soft material between the depths of 30 and 65 ft and virtually no resistance to the penetration test (U.S.B.R., 1960). Only slight firmness was shown in the silt and fine sand above 30 ft, and the penetration resistance showed a gradual increase below depth 65 ft in alternating layers of clays, silts, and sands with another soft clay layer at 100 to 110 ft. Sands and silts of higher penetration resistance were found below the 110 ft depth.

Since the foundation base was at a depth of 35 ft, and the upper sediments consisted of saturated silts and fine sands (with the water table within 5 ft of the surface), an extensive excavation and dewatering procedure was required (Fig. 1), to permit pile placement. The resulting structure and pile foundation with respect to the soil conditions are illustrated in Fig. 2.

TEST PILES

Four test piles were driven and load-tested prior to preparing construction specifications. Because the upper 35 ft of material would be excavated during construction, the test piles were driven inside a hollow steel casing, 5 ft in diameter, which was installed to plant depth. Therefore, the pile tests were performed only in the subsoils of the actual structure foundation. The test piles were loaded to at least twice the probable design load of the plant using the standard test procedure (A.S.T.M. designation, D1143-61T) and reloaded to three and four times this load. One hundred ton loads applied to two piles were used to represent a possible negative friction, dragging condition that might develop if the soft sediments at a depth of 40 to 65 ft were sensitive enough to settle when disturbed.

There are many arbitrary and empirical rules for judging allowable working loads based on pile test results, but none has been established as a standard. The criteria used for these tests were given by Chellis (1951), and are of two basic types. (1) Failure occurs at the load where settlement increases in appreciably greater proportions than the load

FIG. 1. Aerial view showing broad area of the excavation.

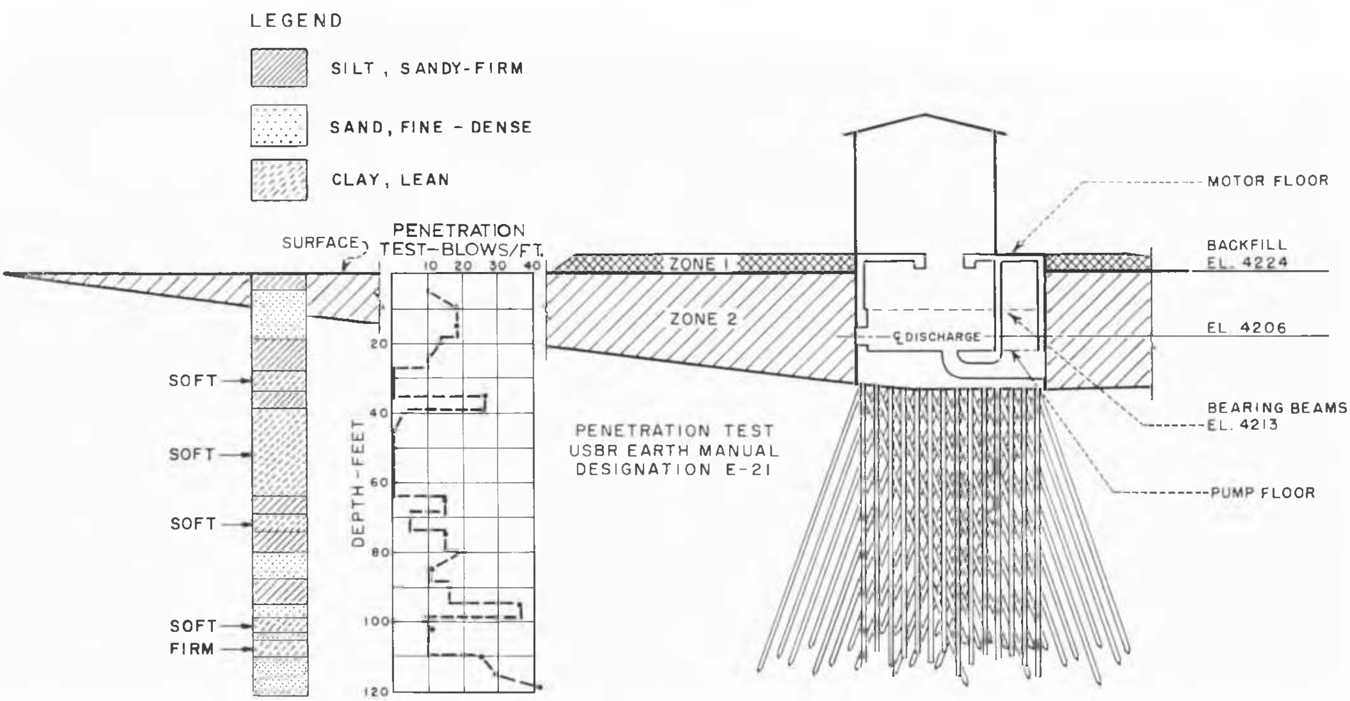

FIG. 2. Pumping plant elevation view showing pile foundation and soil conditions.

increases. (2) The ultimate allowable load is considered to occur when settlement reaches certain maximum values based on several restrictions, such as: (*a*) total movement of no more than 1 in., (*b*) total movement of no more than 0.01 in./ton of load, and (*c*) a net settlement of no more than 0.25 in. after the load is released.

Failure did not occur during the pile tests (Gibbs and Pettibone, 1961) and it was decided to drive the piles for the actual structure into the firmer material below the lower soft clay layer reaching depths of between 70 and 80 ft below the base of the structure. Giving consideration to group effect on computed pile strength, possible increased loads due to negative friction in the upper soft clay layer, and long-time loading effects on the lower clay layers, it was concluded that the pile foundation would adequately support the structure.

PLANT CONSTRUCTION

The necessary excavation was as illustrated in Fig. 2. Laboratory tests of the materials above the plant base, which were saturated silts and fine sands, indicated such low stability that excavation slopes of 7½:1 were required and 10:1 was specified along the discharge line. This resulted in the extensive excavation area (about 600 ft in diameter) and dewatering to a depth of 40 ft. During construction of the plant, all of this material was backfilled and five additional feet of material were added to provide a finished surface around the plant at a level even with the motor floor.

After completion of the pile placement and the preparation for the concrete base, six settlement benchmarks were installed in the subsoil between piles, and six settlement observation points were installed in the base floor. Settlement observations were started at that time and are continuing at the time of writing. As the lower structural portions of the plant were constructed, settlement appeared to be only minor and was attributed to strain of the piles and, possibly, heave that occurred during placement. However, after about 3 months of construction, settlement increased at a more rapid rate. This caused considerable concern, because the allowable limits of differential settlement are obviously small to satisfy the mechanical operation of the plant's large pumping equipment.

Many questions were raised because, as mentioned previously, the pile tests before construction indicated a supporting capacity well within the allowable limits, and the estimated settlements based on the pile tests were insignificant. As observations continued, there were abrupt changes in rates, and at one time a brief upward movement was noted. To add to the questions, two earthquakes of moderate intensity occurred in the area during this time (but these were later concluded to be no consequence to the settlement). After settlement had reached 0.21 ft (2.5 in.), Bureau engineers inspected the plant to make a thorough analysis of all loading events. In reviewing the records of construction, they noted that several of the load changes during construction to that time had distinct correlation to settlement changes, and these loads could be of much greater consequence than the structural loading of the plant. For example:

1. Dewatering lowered the groundwater level about 40 ft, which would increase the effective overburden pressure. However, dewatering was probably gradual and just ahead of excavation.

2. Excavation to a depth of 35 ft relieved considerable pressure. This excavation was so extensive—a width of more than six times the length of piles—that its effects could easily extend beyond the soil through which the piles passed and into subsoils at greater depth (Fig. 2).

3. As the plant was constructed and backfilling operations started, the relieved pressure mentioned above was reapplied and similarly could have influence in the deeper subsoils (backfill, Zone 2, in Fig. 2).

4. Groundwater was allowed to rise which moderately counteracted the backfill loading with an uplift pressure. However, to facilitate the pump installations in the plant, the level was maintained for some time at the lower floor in the vicinity around the plant.

5. After completion of the motor floor, the backfill was increased to 5 ft above the original ground surface (Zone 1 in Fig. 2).

If the excavation for this structure had consisted of the steep slopes usually used for building excavations, the effects of pressure changes would certainly be less, and would occur

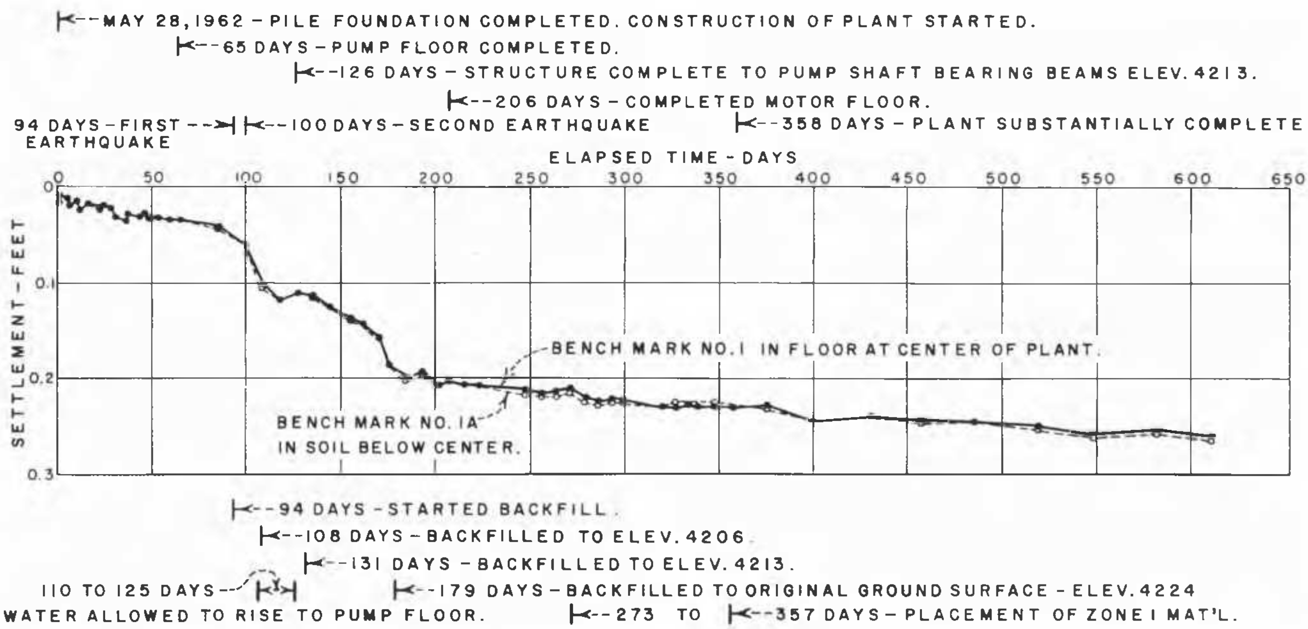

FIG. 3. Settlement records of the pumping plant.

mainly in the soils just below the structure and through which the piles passed. The extensive area of this excavation and the resultant large volume of backfill caused these effects to extend well beyond these soils and actually encompass the whole pile foundation.

SETTLEMENT DISCUSSION

Fig. 3 exemplifies the settlement records and their association with major construction events as they were obtained from the construction record. It is noted that, as backfilling started on Day 94, the abrupt increase in settlement rate began. After backfilling to the centre of the discharge tubes on Day 108, groundwater was allowed to rise to the level of the pump floor. It apparently was the cause of a slight rise in movement. When backfilling was continued, the higher rate of settlement resumed. When the Zone 2 backfill was finished on Day 179, the settlement rate decreased and the foundation appeared to become stable. This condition exists at the present time, the movement becoming gradually less until it has virtually stopped. When the additional 5 ft of Zone 1 backfill, for a relatively small area around the plant, was added on Day 273, an additional settlement was observed.

This study of settlement was of particular interest because records are more complete than usually obtained on a structure resting on a soil foundation. Observation covered the total period of construction activity. The soils were critical and movement would have been considerably more if piles had not been used. It is apparent that the piles are serving their purpose by adequately resisting movements that would have occurred in the upper soft soils during the process of unloading and reloading as excavation and construction progressed. Although the settlements were sufficient to cause concern, the observations made and their relationship to construction loading changes explain this settlement. When compared to other structures and laboratory tests on soils in this area, these settlements are minor and not considered critical.

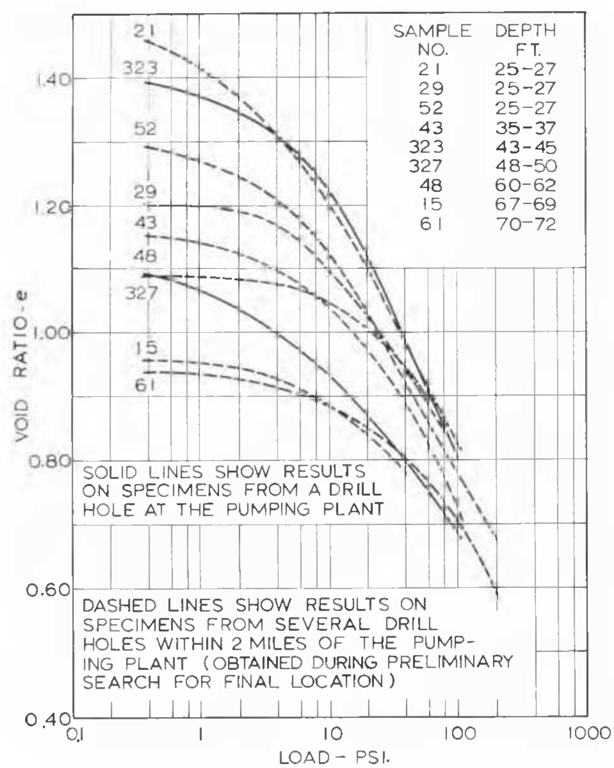

FIG. 4. One-dimensional consolidation test results of the foundation soil.

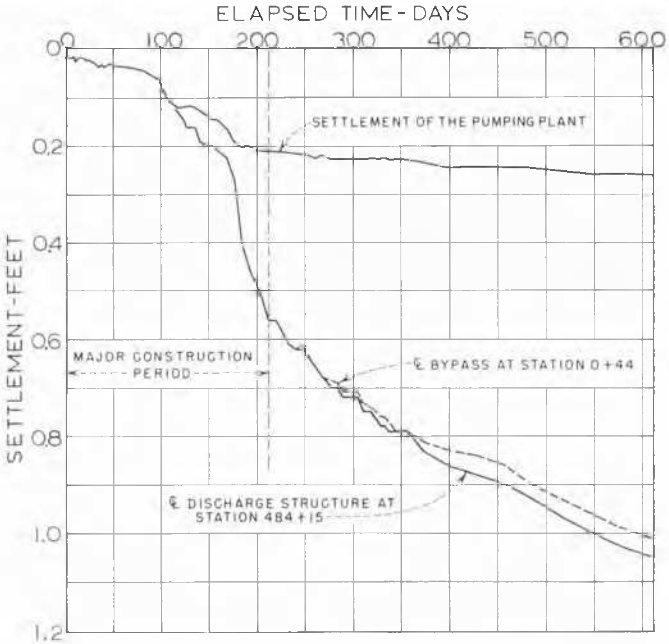

FIG. 5. Comparison of the pumping plant settlement to that of nearby structures that are not founded on piles.

In the Willard Bay area, similar soils are settling several feet as a result of the embankment loads imposed by Willard Dam, a 37-ft-high embankment (Daehn and Esmiol, 1957). The load imposed by this embankment is similar to that of the backfill loads at the pumping plant. Although the pumping plant backfill loads are only slightly greater than those of the original soil, the combination of excavation and backfill has caused a major cycle of unloading and reloading in the relatively short time of about one year.

In the process of investigating the subsoils within a distance of 2 miles of the selected site of the pumping plant, several consolidation tests were conducted on undisturbed samples from different drill holes at depths varying from 25 to 72 ft. The load consolidation results of these tests are shown in Fig. 4. Some of the softer soils from the upper level of 25-ft depth had initial void ratios as high as 1.40 to 1.50. A soil sample from depths 43 to 45 ft in the immediate vicinity of the plant had a void ratio of 1.40. These softer samples consolidated at high values of compression indexes of about 0.450 over load changes from 10 to 100 psi, indicating they are highly compressible. Deeper samples (near 70 ft), from areas rejected as plant sites, were somewhat less compressible, but had compression indexes of about 0.20 over this same load range.

These values of compression index indicate that, if piles were not present, the soft upper soils would have settled considerably under the load changes of some 20 to 40 psi that were caused by the excavation, dewatering, and backfilling that took place.

CONCLUSIONS

The conclusions with regard to settlement of the Willard Pumping Plant are illustrated in Fig. 5. When the settlement of the plant is compared to that of the nearby bypass and discharge structures which are not pile supported and which involved considerably lower load changes, the critical nature of the foundation becomes apparent. It is obvious that, if the pumping plant had not been pile supported, its settlement would have been greater than those of the bypass and discharge structures.

The pile foundation supported the structure on firmer soils at greater depth, but did not completely prevent settlement caused by the extensive backfill operation shown in Fig. 2. Although the backfill load is only a slight increase over previously existing loads, the soils are so critical that reloading consolidation is significant and is the obvious reason for the rapid settlement during construction. The distinct relationships of these loads to settlement are shown in Fig. 3. After completion of construction, it appears that the plant is being adequately supported by the pile foundation.

These settlement records are of special interest because they provide a rare example of settlement observations made during as well as after construction. The critical nature of the soil emphasizes the movements, making the effects of the different phases of construction distinctly apparent. Therefore, these observations should be valuable as a future reference and increase our knowledge of the behaviour of critical soil foundations when loaded over unusually extensive areas.

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