Submerged foundations for 100 000 ton oil tanks

A. J. LEGGATT & G. E. BRATCHELL

Mr G. S. Crawley, Leslie Crawley & Partners Ltd

It is a fundamental of the Authors' choice of method of construction that the replacement gravel fill was obtained from a nearby pit owned by Esso Petroleum Co. As the Contract involved the replacement of approximately 160 000 m^3 of soil, there was presumably a large saving in cost by utilizing this nearby source. The replacement method has great potential in areas where poor soil conditions exist and it would enhance their Paper if the Authors would comment on the relationship between the cost of obtaining replacement material of the maximum depth of poor soil at which the replacement method is considered to be more economical than the conventional piling solution.

42. Some difficulty was apparently experienced in obtaining a good clean bottom to the excavation. Presumably, such difficulties were not envisaged at the design decision stage. Were the necessary modifications to the suction dredger sufficiently successful to obviate the further need for bottom cleaning by the expensive and arduous air lift process? In this connexion, bearing in mind the difficulties found with bottom cleaning and with the inspection, would the Authors give some indication as to the degree of cleanliness required and as to the practicability of achieving this by the displacement of the replacement gravel fill, particularly in view of the low final density achieved?

43. The use of penetrometer testing to provide a check on the compaction of the fill apparently resulted in an easier and cheaper method of checking than large scale standard penetration testing. Could the Authors provide details of the testing equipment used?

44. It would be helpful if the Authors would comment on the established criteria referred to in § 23 and whether or not these criteria relate to the correlation between SPT and penetrometer results, as it is also stated that there were no means of directly correlating the two.

45. What was the final density achieved in comparison with the natural density of the gravel fill at the quarry? Did the Authors envisage any problems of differential settlement due to the low degree of compaction shown by the difference in the two densities?

Mr T. M. Hart, J. L. Eve Construction Co. Ltd

I was the main contractor's Engineer responsible for construction. Much of the success of the final result stemmed from the intense interest of the three major subcontractors involved in underwater excavation, vibrocompaction and compaction testing. As main contractors we had to organize their methods of working and provide the Engineers with daily records of plotted test results. In spite of the fact that the bases were larger in plan than the Albert Hall, the water area seemed very small when at some time in each excavation there was a dredger, two floating Bailey bridges, up to three portable conveyors operating from the edges, and teams of divers air-lifting fine material or removing obstructions and checking the base for a clean gravel bottom before filling.

47. The dredging sequence for tank 281 shown in Fig. 4 was decided on after

Paper published: *Proc. Instn Civ. Engrs*, Part 1, 1973, **54**, May, 291–305.

experience in tank 282. Owing to the time element it was originally expected that filling would be taking place in tank 282 excavation while the dredger was still excavating in this same hole. The method planned was to excavate in sectors with the filling following the excavation. Unfortunately, the fill, when placed by normal tipping methods, did not behave as expected and two massive underwater slides took place, both of them occurring when 12 500 cu. yd of material had been dozed. Tank 281 was therefore excavated as the Authors described and with complete success.

48. The grading of the fill as specified in Table 1 was not in fact found available at the borrow pit and the material placed had up to 9% of material passing the No. 200 sieve. The original grading specification indicated a good all-in ballast type of material which should have behaved well when tipped into water. I think that the enforced inclusion of these finer materials caused the fill to behave in the way the Authors describe.

49. Many trial holes were made in the borrow pit at the start of the work to find material with fewer fines and an investigation was made to see whether some form of washing plant could be set up to remove the finer material. On balance, the floating bridge method of tipping was cheaper and quicker and proved trouble-free, although in the early stages the drivers of the large tipping lorries approached the bridge ends in reverse with some trepidation.

50. Safety was a considerable problem and great credit is due to the site staff that not one single reportable accident occurred on the works. Even bulldozer drivers wore life-jackets, all cabs were removed and the wearing of rubber boots was forbidden near the open excavation. There is not one operative on my company's staff who would not welcome the chance to work on a project of this type again which would indicate the team spirit built up on the site.

51. I hope this Paper will stimulate further design work for foundations of this type, the application of which is not limited to oil tanks.

Dr A. D. M. Penman, Building Research Station

The Authors are to be congratulated on saving two large steel tanks by floating them to new satisfactory foundations. The design of foundations for oil tanks on soft alluvium, initially too soft to support the full tank, provides interesting soil mechanics problems. Solutions, in order of cost, include (*a*) piles to firm stratum, (*b*) rockfill piers, (*c*) consolidation of the natural soil by surcharge, (*d*) consolidation of the natural soil by the weight of the tank itself. Method (*d*), first choice in the Authors' decision pattern, requires the greatest soil mechanics skill and offers the greatest potential saving. I was sorry to find that the Authors did not have sufficient time to be able to use it. I have used it for smaller tanks on more favourable soil at Teesmouth and drawn comparisons between methods (*a*), (*b*) and (*d*).[1]

53. A major problem with this approach is to know the maximum tank deflexion that can be used. The consolidation and lateral displacement of the soft soil can be replaced by a sufficient thickness of pad under the tank, so that its base does not sink below the required level. The fact that the centre will settle much more than the edge can be allowed for by making the pad thicker towards the centre, so that initially the plates are dished upwards. However, will a tank tolerate changing shape from, say, an upward dish of 2 m at the centre, to a downward dish of 2 m at the centre plus a differential tilt of 0·3 m? Flotation of the tanks as described by the Authors suggests that they can accept considerable distortion. They say in § 25 that the relatively thin mild steel bottom plate will balloon upwards to the extent of some 10 ft in the centre. Did it? In replying to the discussion on our Paper[1], we drew attention to failures that have occurred by plate or weld fracture in the bases of tanks built with an initial downward dish. Settlement increased the dish to failure. Can the Authors say how much distortion their large tanks suffered during flotation and could they expand on the results of the strain gauge monitoring?

54. Details of the settlements measured on the four concentric rings (§ 30) would be valuable, together with settlements caused by the 8000 ton surcharge (§ 22).

55. The Authors state in § 35 that the pore pressures in the Barton clay behaved as expected. Could they give records of the changes measured during loading and unloading the tanks?

Messrs Leggatt and Bratchell

The fundamental advantage in using the gravel pit as a source of fill was that it was nearby and not so much that it was owned by our Clients. The latter fact certainly made things easier but, on a strict account, we consumed our Client's assets, for certainly they would otherwise have use for the gravel in the future, and this loss was taken into account in the decision making. The full cost of hauling the gravel some two miles to the site had to be paid and thus the only true cost saving was due to the relative proximity of the source. Bearing in mind that materials other than gravel can form satisfactory fills, it would be unusual to find that no fill is obtainable within an economic range for a particular site.

57. The cost of obtaining fill is not usually the dominant parameter affecting the optimum depth of the replacement method and each problem must be evaluated individually; nevertheless, it is interesting to contemplate the effects of depth of poor soil on the costs of other aspects of the work. Increasing depth will adversely affect the cost for geometric reasons. On a very wide excavation the effect may not be too great. In principle, suction dredging can be carried out at any depth although some adaptation of standard plant may be required below 35–40 ft. Diving work, so far as it would be necessary, would become more difficult and much more expensive with depths below 40–50 ft, the difficulties becoming severe below say 120 ft. Apart from the geometric increases referred to earlier, the cost of fill and its placement would not be affected by depth although its mechanical compaction would be. In summary, we suggest that soil replacement can be considered as a technically feasible alternative to conventional piling at least as far as a depth of 50–60 ft of alluvium.

58. It was certain that the adaptation to the dredger described in the Paper produced a marked improvement in cleanliness of the bottom. We attached importance to cleaning up the soft alluvium particularly in the outer zone of the circular plan. Even the thinnest layer of soft material could have formed a potential slip plane and caused edge failure of the foundation. Provided that one had a certain means of control of cleanliness, and in practice this is very difficult, there would be a theoretical justification for allowing a thin layer of soft material to remain in the central zone of the excavation, well removed from any potential edge failure. The criterion of acceptance here would be the consolidation settlement of the remaining layer, but it would be almost impossible to be sure that the residual alluvium was of uniform thickness or that it would remain thus during deposition of the fill material. In practice, by far the best course, bearing in mind tolerance difficulties with dredging, is to take out all the alluvium and, if the technique is correct, this is not difficult.

59. The penetrometer was a Soil Mechanics Ltd machine comprising a $1\frac{1}{2}$ in. dia. rod driven by a weight of 140 lb. Further details can be obtained from that company.

60. With regard to correlation of penetrometer and SPT results, by 'direct correlation' we meant the ability to obtain the two separate test results on one identical column of soil. The best we could do was to carry out boreholes with SPTs at selected points in a general area covered by the penetrometer tests. We were also able to obtain some useful evidence from the test mound referred to in § 22 because penetrometer and SPT tests had been carried out on the fill beneath.

61. We believe that the final density achieved was approximately 70% of the in situ density at the quarry, the latter being extremely dense. The settlements in the fill are given in Table 2 of the Paper and have been accepted.

62. We are grateful for **Mr Hart**'s contribution. Safety is rather a dull subject

until an accident actually happens. Nevertheless, the continuous and diligent concern with safety matters which pervaded this project paid off handsomely in the splendid record which Mr Hart reports. Despite the pressures and urgencies of the work, a report on accidents and safety measures was always the first item at site progress meetings.

63. Apart from the slowness of the method, there are other reasons for rejecting the formation of the foundations by natural consolidation of the existing soils, as stated by **Dr Penman** and as discussed in Fig. 2 of the Paper. The considerable additional settlement involved in the consolidation method would have required a replanning of the tank farm arrangements. There were severe practical limitations on the height to which the tank could be lifted during flotation.

64. We do not have precise information on the ability of these tanks to withstand the bottom deflexion and tilt referred to by Dr Penman but the information could be obtained from the tank manufacturers or from Esso Research and Engineering Ltd. However, it is certain that an oil tank can be designed from scratch to withstand any particular pattern of settlement prescribed for it. In § 28 of the Paper it is suggested that, for future work, closer study of settlement patterns in the design of oil tanks could be advantageous.

65. The reference to the 10 ft of upward ballooning requires further explanation. In theory, the tank would float in less than 1 ft of water if the bottom remained rigidly flat. In practice, the tank just lifted off in about 3 ft of water and the bottom plate was lifted up relative to the tank by about the same amount except near to the tank wall. The 10 ft referred to was the amount of ballooning which might have occurred if air had been introduced beneath the bottom plate, and this was thought to be too risky.

66. The results of the settlements on the four concentric rings, the settlements caused by the surcharge load, and the pore pressures, are all available at Nachsen, Crofts and Leggatt. However, a further paper recording this information is to be presented at the Conference on Settlement of Structures, Cambridge 1974.

Reference

1. Penman A. D. M. and Watson G. H. Foundations for storage tanks on reclaimed land at Teesworth. *Proc. Instn Civ. Engrs*, 1967, **37**, May, 19–42; Discussion, 1968, **39**, Apr., 585–601.