Deep compaction with the Vibro-Wing method

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DURING THE CONSTRUCTION of an extension of the harbour at Rostock, German Democratic Republic, for handling general cargo, a 1.2 million m^3 hydraulic fill has been compacted by the Vibro-Wing method down to a maximum depth of 15m. The extension consists of a 1 250m long wharf constructed of precast concrete caissons and anchored sheet pile walls and a 25 000m^2 storage area designed to carry a uniformly distributed load of 300kPa. Within the area are also several portal cranes and a number of warehouses. The method has also been used below water to compact the sand beneath the concrete caissons. The work is seen in progress in Fig. 1.

The Vibro-Wing unit is shown in Fig. 2. It consists in principle of a 15m long steel rod which has been provided with a number of wings welded to the rod. The unit is driven down into the fill using a high capacity vibratory hammer and then slowly pulled out during continued vibration. The time for driving and withdrawal of the unit is about one and five minutes, respectively, the sand being compacted both during the driving and when the unit is retrieved. The time required for compaction is thus short compared with other deep compaction methods such as dynamic compaction using heavy weights or vibro-flotation.

Compaction was done in a triangular pattern with a spacing of 1.5m to 5m between insertion points. Effect of the compaction is controlled preferably by static cone penetration tests (CPTs) using an electrical or mechanical cone penetrometer; it is advantageous to measure both the point and the shaft resistance. The weight sounding method can also be used. The penetrometer tests indicated that a high relative density can be obtained in medium to fine sand.

In Fig. 3 is shown the results from cone and standard penetration tests carried out before and after compaction using the Vibro-Wing method. A considerable increase of the penetration resistance was observed at all levels except close to the ground surface above the ground water level.

The cone penetration tests indicate that the thickness of the poorly compacted surface layer is relatively small (1.0-1.5m) with the Vibro-Wing method. At the ground surface compaction therefore has to be supplemented by other methods; compaction of this layer is normally done with a 8-10 ton vibratory roller after the deep compaction.

Compaction mechanism

Pore water pressure increases rapidly during the compaction around the Vibro-Wing unit as it is driven down into the soil. This increase of pore water pressures has been observed with pore pressure gauges placed at different levels in the soil. The effective stress is thereby reduced and individual sand particles can be displaced; thereby a higher relative density can be obtained. When the pore water pressure corresponds to the total overburden pressure the effective stress in the sand is reduced to zero and the soil is liquified. Liquefaction occurs at first locally around the vibrating wings. It spreads gradually as the pore water pressures increase around the vibrating unit.

The high local pore water pressures around the wings cause a mainly radial flow of water to the surrounding soil. There is also an upward flow, at first locally around the rod which can be observed at the ground surface. The resulting reduction of the water content causes a reduction of the void ratio and of the porosity. Accordingly the relative compaction and the relative density of the soil are increased. For a saturated soil the reduction of the porosity and the resulting increase of the relative density correspond to the reduction of the water content.

The most important effect of the compaction is the increase of the pore water pressure by the vibrations and the reduction of the effective stress in the soil. The size of the liquefied zone around the Vibro-Wing unit is affected mainly by the permeability of the surrounding soil and the relative density. In the case where the permeability is high (coarse sand) the liquefied zone will be relatively small and localised around the vibration rod because the excess pore water pressures dissipate rapidly. The permeability of a coarse sand can be 100-1 000 times higher than that of a fine sand. Driving and withdrawal of the Vibro-Wing unit has to be carried out relatively rapidly; otherwise the unit may become stuck in the sand or be difficult to pull out. Spacing of the insertion points should be relatively small in this case.

In fine sand a relatively large zone is

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Fig. 1. Vibro-Wing work in progress on the hydraulic fill at Rostock

Fig. 2. The Vibro-Wing equipment

affected around the Vibro-Wing unit. A comparatively long time is required for the dissipation of the excess pore water pressures, the reduction of the water content and the increase of the relative density. Driving and withdrawal should be done relatively slowly to allow sufficient time for the dissipation of the excess pore water pressures and the reduction of the water content.

If the soil contains layers with low permeability, which is often the case in hydraulic fills, the effectiveness of the method is increased if the sand is relatively coarse since a longer time will be required for the dissipation of the excess pore water pressures. A larger zone will thus be effected by the liquefaction compared with the case when the soil is uniform.

The mechanism of the compaction through local liquefaction implies that an hydraulic fill will be considerably more difficult to compact above than below the ground water level provided the soil is not watered. The effective stress is increased above the ground water level due to the false cohesion of the soil. This false cohesion can be eliminated by watering.

The hydraulic fill in the concrete caissons was also compacted by the Vibro-Wing method. However the caisson walls reduced the drainage and the consolidation of the fill during the vibration. The excess pore water pressures were higher and the size of the liquefied zone was increased. Since radial drainage was reduced by the caisson walls a longer vibration time was required compared with the case of free radial drainage.

The pattern and order of insertion of the Vibro-Wing unit are particularly important for silty sand when the silt content is relatively high and a long time is required for a complete dissipation of the excess pore water pressures. For these soils it would be advantageous to carry out the compaction in stages. First, a relatively large spacing should be used and a relatively long vibration time. After a few days to allow the soil to consolidate the compaction is repeated. The spacing of the insertion points is then reduced, as well as the time required for the vibration. The procedure is repeated until a sufficiently high relative density has been obtained which can be checked with static cone penetrometer tests.

The efficiency of the Vibro-Wing method is also affected by the size and location of the wings. In coarse sand the wings should be relatively short and be placed relatively far apart because of the high permeability of the soil. If the wings are large it will prove difficult to retrieve the Vibro-Wing unit because of rapid dissipation of the excess pore water pressures in the soil. A relatively intensive vibration will be required to cause local liquefaction of the sand. In fine sand relatively large and closely spaced wings can be used in order to increase the effectiveness of the method.

The compaction locally increases the lateral earth pressure in the soil which may even approach the total overburden pressure. This means that adjacent structures have to be designed to resist locally a relatively high lateral earth pressure especially in fine or silty sand.

The driving and retrieval of the Vibro-Wing unit can be regarded as a penetration test. The pore water pressure is increased during the driving which reduces the driving resistance. By measuring the time required for the driving of the Vibro-Wing unit at a given

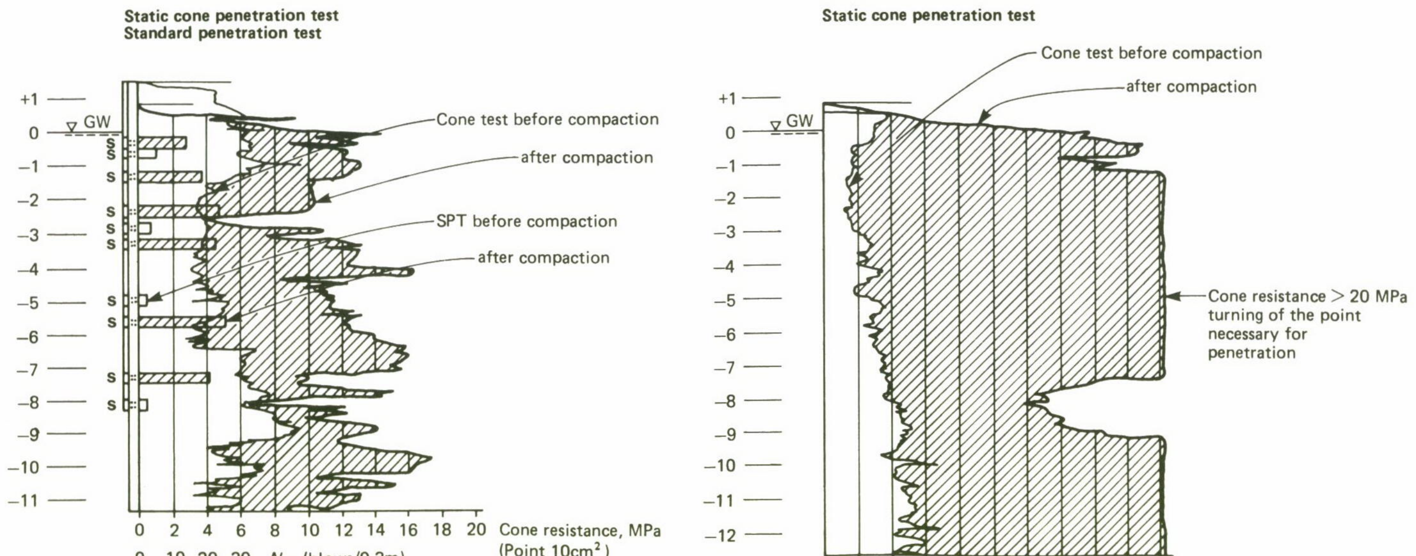

Fig. 3. Static cone and standard penetration test results before and after the Vibro-Wing compaction at Rostock. The diagram on the left refers to the hydraulic sand fill back of the caissons; on the right, to the fill inside a caisson

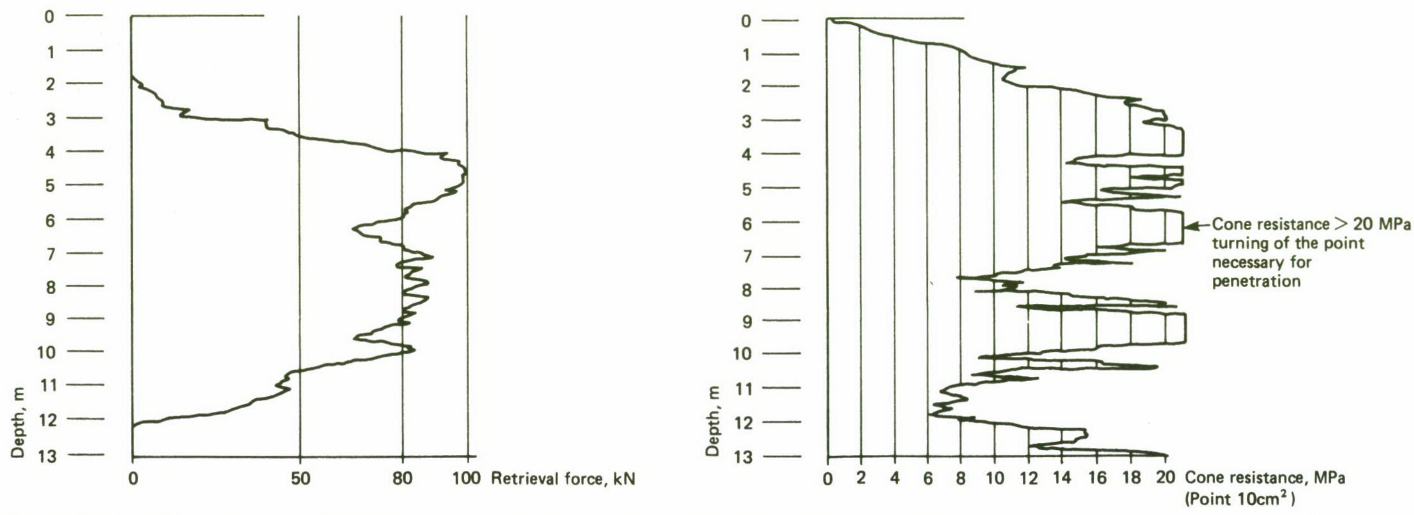

Fig. 4. Retrieval force (less weight of the equipment), showing its relationship to the penetration resistance

applied axial load (the weight of the hammer) and the variations of the penetration rate, deviations in the composition of the soil can be detected.

The force required to retrieve the Vibro-Wing unit at a given rate is measured. This force is an indication of the pull-out resistance when the retrieval rate is kept constant and of the friction resistance along the wings and the rod. This force is thus indirectly a measure of the relative density of the soil. The friction resistance increases gradually as average lateral earth pressure increases in the compacted soil and the excess pore water pressures dissipate. In Fig. 4 is shown a comparison between the retrieval force and the penetration resistance.

The greatest advantage of the method lies in the speed and low cost compared with other deep compaction methods. Another additional advantage is that the thickness of the poorly compacted surface layer is relatively small. A limitation of the method is that water may in many cases have to be added above the ground water level. The method has not so far been applied in silty or clayey soils when the content of fines exceeds 5-10% or in coarse sand or gravel. The permeability of silty or clayey soils is probably too low for the method to be efficient; the time required for consolidation of the soil would probably be excessive.

It should be possible to compact medium to fine sand down to a depth of at least 40m. In general it is only required to compact a soil below a depth of 20-25m in exceptional cases because the compressibility of cohesionless soils decreases with depth and with increasing overburden pressure. The settlement of cohesionless soil is in general small and negligible below a depth of 20-25m for most conventional structures. Also the risk of liquefaction caused by earthquakes is reduced with increasing depth and with increasing overburden pressure. Normally the risk is small at depths exceeding 15m even when the relative density of the soil is low.

Applications of the Vibro-Wing method

There are several possible applications of the Vibro-Wing method such as in foundations, harbours, hydraulic fills, dams especially tailings dams subjected to earthquakes, machine foundations and for special structures.

Foundations

There are large areas in many parts of the world where deep deposits of medium to fine sand and of silty sand occur and where the Vibro-Wing method can be used to compact the soil e.g. along coasts or major rivers. The method should be particularly useful in areas subjected to earthquakes, to avoid liquefaction.

Harbours

Wharfs and piers are to a large extent located in areas where there are deep deposits of cohesionless soil and where the relative density is low. The Vibro-Wing method should be especially suited for such structures since compaction is often also required below the ground water level or below water. The efficiency of the method is increased below ground water level or when the compaction is done in water.

Soils along coasts normally have a composition and grain size distribution which suits the Vibro-Wing method (fine to medium coarse sand or silty sand). Clay, muck or peat layers may, however, reduce the effectiveness of the method since these layers act as more or less watertight membranes in the soil. Such layers reduce the drainage and consolidation of the soil. The soil will, however, be homogenised to a certain extent by the compaction which reduces differential as well as total settlements.

Hydraulic fills

Hydraulic fills are used extensively in, for example, Japan and Holland for industrial sites and for housing developments. Other applications include airfields and harbours. The relative density of hydraulic fills is in general low without compaction. In most cases compaction has to be carried out below the ground water level or below water. Preloading, dynamic compaction or the sand pile method are frequently used. However these methods are relatively slow and expensive compared with the Vibro-Wing method for medium to fine sand or for silty sand. Preloading is a suitable method often in combination with vertical drainage in clayey and silty soils where the permeability is too low for the Vibro-Wing method, dynamic compaction or the sand pile method.

Dams

It could be advantageous to use the Vibro-Wing method for earth or rockfill dams which are founded on a deep deposit of medium to fine sand. The method could be used below the upstream or downstream slopes in order to reduce the risk of liquefaction during an earthquake. The main advantage with the method is that the compaction can be done below water or below an existing earth dam since the Vibro-Wing unit can be driven through even a compacted earth fill. The results of the compaction can be checked, e.g. with static cone penetrometer tests.

Tailings from mines are normally stored behind special tailings dams. The coarser fractions are used in the main body of the dam. The tailings in the dam structure are not compacted at present. A number of landslides have occurred which have been caused by liquefaction in, for example, South Africa (gold mines), Great Britain, and USA (coal mines), Canada, Peru, Chile and Mexico. It should be possible to use the Vibro-Wing method to increase the stability of existing tailings dams, especially during earthquakes.

Machine foundations

Another possible area where the Vibro-Wing method could be used is for machine foundations which otherwise would have to be placed on piles to reduce settlements caused by vibration. The damping of a machine foundation founded on piles is often very low and the vibration level is often high since a gap is normally formed between the piles and the surrounding soil. A large number of machine foundations in Sweden which are supported on piles have experienced difficulties. By placing the foundation block directly on the compacted soil settlements can be reduced and excessive vibrations can be avoided.

For such foundations located on slowly consolidating soil, e.g. clay, a very economic solution could be to excavate the clay under water in order to keep the slopes stable. After that the excavation could be filled with hydraulic sandfill in one layer up to and above the groundwater level. From surface the fill could be compacted with the Vibro-Wing method and the foundation placed directly on the compacted soil.

Special structures

The Vibro-Wing method can be used also to compact medium to fine sand in caissons in order to increase stability. The compaction frequently has to be done below water.

Other possible applications of the method are the artificial islands that are constructed of dredged material in the Arctic for the drilling of oil. Such islands are also used in water to provide a link between a bridge and a tunnel. Other applications are offshore structures, such as drilling and production platforms, lighthouses, moorings etc. constructed on sand. However the relative density is often sufficiently high so that any additional compaction of the soil is not required.