Panel discussion: Some geotechnical innovations
Débat de spécialistes: Quelques innovations géotechniques

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ABSTRACT: A novel methodology is applied in order to explain and predict soil behaviour during geotechnical operations. Understanding the physical soil mechanics through observation and interpretation of experimental and analytical results has played a fundamental role in developing the concepts presented. The successful application of the approach, which is based on the concept of hypoplasticity, is exemplified by field tests, installation of different pile types, dynamic and static soil compaction and sand anchors.

RESUMÉ: Une nouvelle méthodologie est appliquée pour expliquer et prédire le comportement du sol pendant des operations géotechniques. La compréhension de la mécanique du sol du point de vue de la physique en aide de l'observation et l'interpretation des resultats expérimentaux et analytiques a joué une rôle fondamentale pour le developeement des concepts présentés. Pour démontrer le succès de l'application de la méthode, qui est basée sur le concept de l'hypoplasticité, quelques exemples des tests de camp, de l'installation de différents types de piles, de la compactage statique et dynamique du sol et de l'ancrage de sable sont données.

1 INTRODUCTION

There is still a great potential for geotechnical innovations. Physical soil mechanics plays a keyrole, leaving aside computer-oriented conventions and focussing more on the behaviour of soils during geotechnical operations. This will be shown by considering:

- Static expansion or penetration of cylindrical bodies
- Static penetration with torsion
- Dynamic penetration and deep vibratory compaction
- Penetration, densification, and wave propagation with pore water
- The role of gas bubbles in soft ground
- Stuffing granulates into soft ground
- Granulate anchors

2 STATIC EXPANSION OR PENETRATION OF CYLINDRICAL BODIES

The expansion of a cylindrical body has repeatedly been tested in calibration chambers (Manassero 1989, Schnaid 1990, Nutt 1993). It comes up to increasing the internal radius r_i so that the radial pressure p_i also increases there (Figure 1).

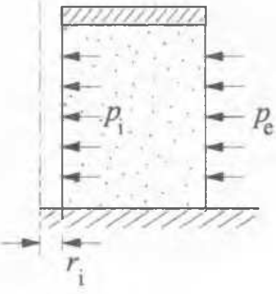

Figure 1: Cylindrical expansion in a calibration chamber

p_i tends to a limit value p_ℓ asymptotically which is determined by the far-field pressure p_e and void ratio e and the initial ratio of pressure components. p_ℓ is almost independent of whether the cylinder is installed prior to or after placement of sand. Practically the same dependence of p_ℓ on p_e and e and independence of placement is predicted by means of a hypoplastic constitutive relation (Cudmani and Osinov 1997). The material parameters for this prediction have been determined from granulometric properties only which are correlated with hypoplastic parameters (Herle 1997). This is an example of erasing the historical element of sand which was first realized by Clarke Maxwell (Darwin 1883). Details of a state produced by placing a pressuremeter are swept out by expansion both in reality and in our hypoplastic model. One can thus determine the void ratio from the limiting expansion pressure if depths and granulometric properties are given (Figure 2).

The same principle holds for static penetration. The cone penetration resistance q_c in calibration chambers was found to

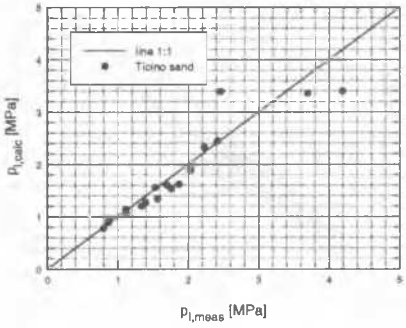

Figure 2: Comparison of the cylindrical limit pressure measured in calibration chamber and calculated using hypoplasticity for the Ticino sand

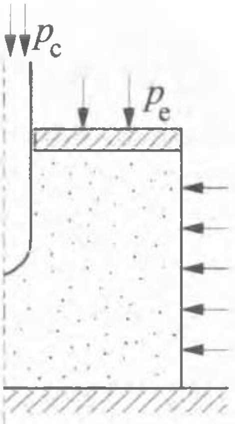

Figure 3: Cone penetration test in a calibration chamber

depend on far-field pressure p_e, void ratio e (Figure 3), and pressure component ratio in general. A simplified model for this case is the expansion of a spherical cavity calculated using hypoplasticity (Cudmani 1996a).

An adaption to the conical shape was obtained by comparing with calibration chamber results, and also by finite element calculations in a few cases. The dependence of the calculated limit pressure p_c on p_e (i.e. depth) and relative density I_d coincides with observations so that I_d can be determined if the granulometric properties are sufficiently known (Figure 4).

The hypoplastic constitutive model describes changes of effective stress components during rearrangement of grain skeletons. Its parameters are easily explained and determined from granulometry (Herle 1997). The critical friction angle φ_c is obtained from shear or slope tests. The granulate hardness h_s, lying between about 10 MPa for caoline and 10 GPa for round quartz grains, is determined from oedometer tests. These give also an exponent n ranging from ca. 0.2 to 0.5 describing the pressure dependence of stiffness. The void ratios of critical state and maximum densification, e_c and e_d, are needed for one reference pressure. A further exponent α ranging from ca. 0.10 to 0.25 describes peak friction and dilatancy; it is determined from triaxial tests and estimated from the angularity of grains. The hypoplastic relations describe the dependency of stiffness matrix and strength for the very wide range of stress components and void ratios. The latter are thus state variables which have to be known for an initial state.

The combination of expansion and penetration is realized by a bored pile with an expander body, and similarly with grouted anchors in cohesionless soils. Shear localization does not occur in these cases as long as dilatancy is suppressed by pressure increase. We leave aside the opposite case for simplicity although it cannot be excluded (Gudehus 1997).

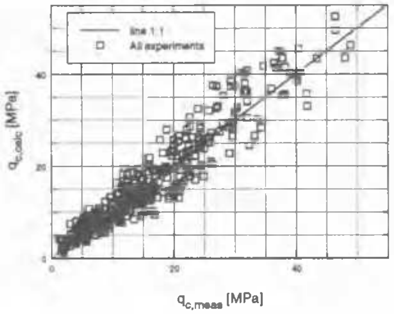

Figure 4: Comparison of the cone resistance measured in calibration chamber and calculated using hypoplasticity for the Ticino, Leighton Buzzard, Monterey, Hokksund and Toyoura sand

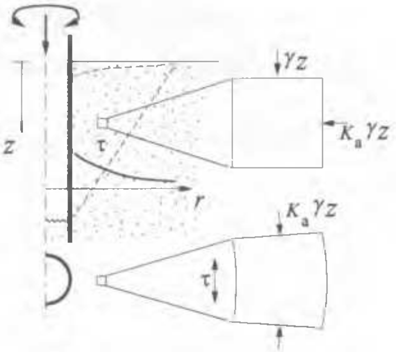

Figure 5: Static penetration combined with cyclic rotation of a tube in cohesionless soil

3 STATIC PENETRATION WITH TORSION

Turning now to the installation of piles in cohesionless soils, we consider first the penetration of a tube by a static axial force combined with cyclic torsion (Figure 5).

Numerical calculations using the hypoplastic constitutive relations show that shear cycles lead the surrounding soil towards an active state near the tube, whereas outside a conical zone the pressure components remain nearly as before. The cycle-wise densification leads to an increasing settlement funnel, which we have likewise observed in large-scale model tests. Similar settlement depressions have been observed during the placement of bored piles in loose to medium-dense cohesionless soils. They can thus not be attributed to the flow of soil to the excavated bottom and are rather inevitable with this technology.

Mechanisms of displacement and densification with torsion can be understood with the so-called Raskatchik (Figure 6). This device with eccentric cones was developed by the Institut of Mining, Siberian Division in Novosibirsk. It is screwed into the ground with a rather low axial force. Increase and decrease of radial and hoop stresses are produced in the ground which is thus densified without the increase of mean stress observed in the previous case of monotonous expansion or penetration.

This mechanism is again modelled by finite element calculations with hypoplastic constitutive relations. Of course, details of cones or of screws with other shapes need not be modelled; they are rather unimportant for the torque and axial force due to the memory effect outlined above.

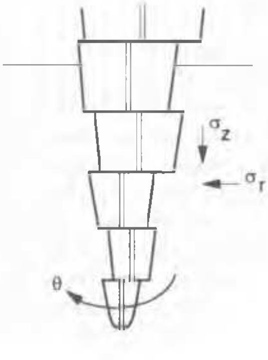

Figure 6: Densification of the ground with the Raskatchik device

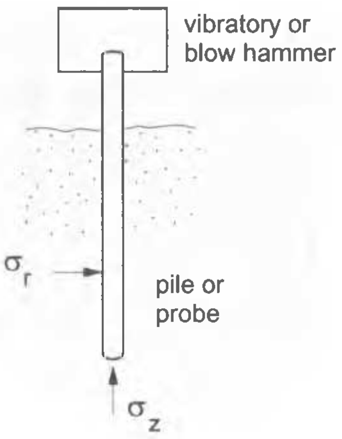

Figure 7: Driving of a pile by vibration or blowing

4 DYNAMIC PENETRATION AND DEEP VIBRATORY COMPACTION

The driving of a pile, or a penetrometer in the ground, is achieved by a attaching a vibratory or blow hammer to it (Figure 7). The shaft and tip resistance is lower than for static penetration as the pressure increases are repeatedly relaxed by the propagation of high amplitude waves in the neighbouring soil.

The radial and the hood pressure are thus always close to the earth pressure at rest, and the tip and shaft resistance never reaches the static penetration resistance. Mechanical models for the penetration mechanism with repeated blows or vibrations have been worked out in detail and verified by field observations (Cudmani 1997). The relative density can thus be determined not only from static borehole expansion or penetration, but also from the velocity of penetration in a vibratory or blow sounding if granulometric properties are given. A novel pneumatic vibratory device was developed for this purpose (Cudmani 1996b).

Deep compaction of cohesionless soil by a vibratory device could also be clarified in some important details. Similarly as with the Raskatchik or a screw pile, nearly cyclic stress changes in the soil around the tumbling vibrator lead to a densification. Different from the static case, the stress changes are propagated via longitudinal and transversal waves. The spectrum of ground velocities measured with geophones was observed to be different in free 3 directions (Förster and Muche 1997): whereas for the radial component the spectral maximum is at the frequency of the vibrator, the maximum of the vertical and circumferential velocities is at twice the excited frequency.

This can be explained by considering cyclic shearing of a medium dense to dense soil under constant normal pressure (Figure 9). Due to the change of contractancy after shear reversal to dilatancy during continued shearing, each shear cycle causes nearly two cycles of volumetric strain. Repeated cycles lead the sample towards a state of maximum densification for the given pressure except for very large shear amplitudes where the material is substantially and repeatedly dilated. This mechanism is clearly observed with resonant column tests (Huber 1997): dense samples show the butterfly-shape change of height as in Figure 9, and an axial vibration with twice the excited frequency.

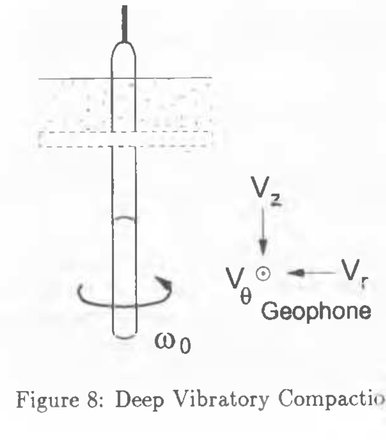

Figure 8: Deep Vibratory Compaction

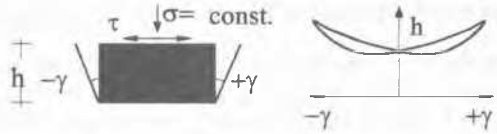

Figure 9: Cyclic shearing of a dense sand probe under constant normal pressure

In the field near a deep vibrator device, the radial velocity is rather directly excited, whereas the vertical and circumferential velocities are induced by dilatancy and contractancy with double frequency. This mechanism is more marked towards the end of densification and should enable an on-line field control.

5 PENETRATION, DENSIFICATION AND WAVE PROPAGATION WITH PORE WATER

The influence of the porewater in submerged soil was omitted in the previous sections for sake of simplicity. The pore pressure during static penetration can be measured at the probe. Excess values clearly indicate the influence of fine particles and thus delayed dissipation. The penetration resistance is also reduced by excess pore pressure with water or air flushing, but calculation models are not yet apt for practical use. The interpretation of penetration sounding and the prediction of dynamic large-scale penetration depends much more on engineering judgement therefore. Only trends and orders of magnitude may be estimated with calculation models, which again can make use of hypoplasticity.

Semi-quantitative statements can similarly be made for deep vibratory compaction. The successful use of compressed air above the groundwater table shows that the pore fluid may be dominantly gas instead of liquid. Below the groundwater table the behaviour of the grain skeleton is similar as without groundwater, but with lower effective pressure. If the latter is brought to zero for lack of porewater dissipation only pressure waves can be propagated. The vibrator is only stirring the surrounding mud instead of densifying the soil as shear waves can no more be propagated.

Some remarks on wave propagation may be of use here. It has been shown using the a hypoplastic constitutive relation that shear waves in a saturated undrained skeleton always lead to a reduction of skeleton pressure (Osinov and Gudehus 1996). The propagation is impossible in a very loose skeleton under non-isotropic stress in certain directions, indicating spontaneous liquefaction. Repeated propagation of waves always leads to zero skeleton pressure, becoming impossible then. With gas channels and free volume changes, therefore, shear waves induce dilative-contractive waves with higher speed (Osinov 1997, 1997a). The double frequency and speed outlined above is obtained in the vicinity of isotropic stress states. The propagation can get impossible for certain non-isotropic stress states even if the skeleton is not very loose. This unpredictability of propagation indicates deterministic chaos.

6 THE ROLE OF GAS BUBBLES IN SOFT GROUND

Gas bubbles in flooded loose granular ground play an important and rather paradoxic role (Figure 10 (a),(b)). A cylindrical, laterally confined undrained sample (a) gets softer and denser under pulsating total axial pressure p. The effective pressure p' and density are increased with each increase of p, but when p returns to the previous value p' and the height h are lower than before the cycle. The elastic pressurized gas bubbles expand the skeleton which is stiffer than for compression. This change is accumulated so that the skeleton tends to zero pressure, i.e. complete liquefaction may be achieved together with densification. The similar mechanism holds with cyclic shearing under constant total pressure (Figure 10 (c),(d)). Shear cycles induce double cycles of density and effective pressure tending towards liquefaction accompanied by densification. (Details of p' are more complicated than in the comparable case of Figure 10 (b) due to low density and not outlined here.)

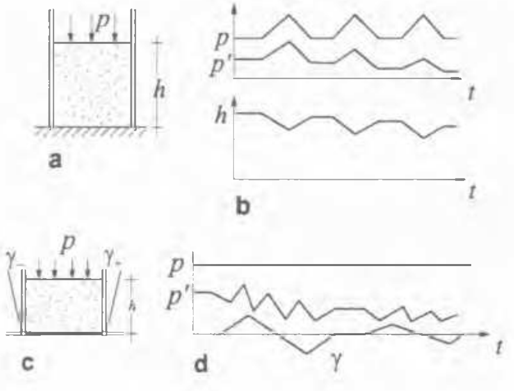

Figure 10: Submerged soft soil with gas bubbles. (a), (b) behaviour under pulsating total axial pressure. (c), (d) behaviour under cyclic shearing

Some field observations can be better explained with this mechanism. Most of natural and industrial fine-grained loose submerged deposits are not fully saturated. Many small-amplitude P- and S-waves and too short intervals for porewater dissipation lead to an accumulation of excess pore pressure with slight densification. With higher amplitudes, as e.g. during strong earthquakes or under offshore structures during heavy storms, a few S and/or P-waves can likewise reduce or even annihilate the effective pressure. (The workability of fresh concrete has the same reason.) With very high amplitudes, as due to an explosion or a falling weight, the single S or P pulse suffices to transform the soil into a suspension.

If the weakened skeleton cannot flow aside at a slope or under surface dead load and has time for drainage water is expelled by the gas bubbles, leading to a familiar densification with strengthening. If, however, drainage is prevented and dead load or soil weight favour sideward flow the gas bubbles are mobilized by further shearing. They can collect to gas cushions under non-liquefied soil cover which then can slide as a hovercraft. The observed higher mobility of flowing debris compared with water flow can thus be explained.

7 STUFFING GRANULATES INTO SOFT GROUND

The deep vibration with bottom feeding by coarse-grained material is well-known. Following our advice, the company Keller made a field test, feeding in fly-ash into an uncompacted wet partly fine-grained fill (Figure 11, principle). Lowering the vibratory device worked as usual, but by rising it and feeding in fly-ash another consolidation occurred: The surrounding soil was cracked, and the passage of porewater towards the fly-ash was also accelerated by suction. We control the increase of shear strength and stiffness with this consolidation by measuring the shear wave speed before and after the operation (which is also done with other methods such as blasting).

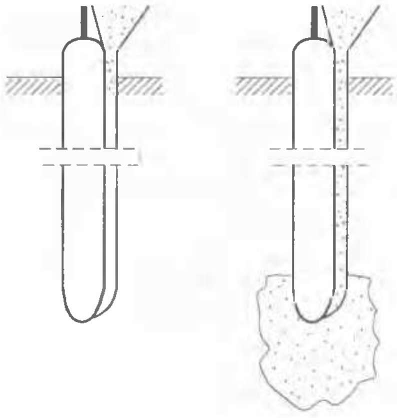

Figure 11: Stuffing of granulate into soft ground using the bypass method

This method is not applicable in the vicinity of the foundations of historical buildings. Instead, we then stuff in mineral, chemically neutral granular material into the soft ground via narrow boreholes by inverted rotation of a continuous auger (Figure 11).

This method has been tested in the field, also under loaded foundations. Practically without additional settlements, the soft ground is densified and partly substituted, and loose foundation masonry is laterally prestressed by stuffing the lateral fill. The historical substance does remain untouched, and no artificial materials have to be added to the soil. Conservational and ecological problems do not arise, sufficient stability and serviceableness is achieved with a low price.

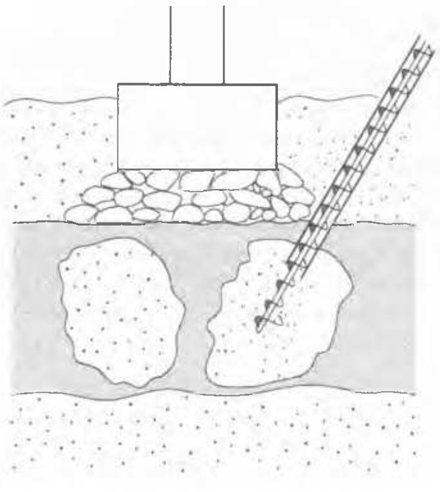

Figure 12: Ground improvement by stuffing in the vecinity of shallow foundations of historical buildings

Similar stuffing is proposed for roads and railway tracks. Depressions, which preferably appear as waves of different lengths, can be compensated by stuffing the softer parts of the soil base. Repetition is scarcely necessary as the resulting ground is denser and less deformable, therefore.

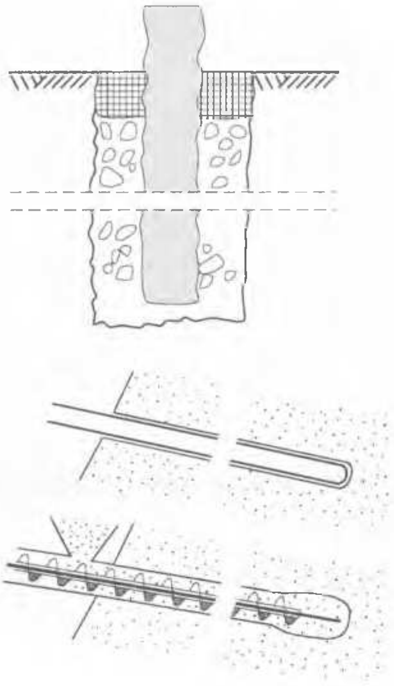

Figure 13: Sand anchors: in Rock (above), in coarse- or fine-grained soils (below)

8 GRANULATE ANCHORS

A rough steel tendon can be linked to competent rock by filling the gap with dense sand (Figure 13). As was first shown in Novosibirsk (Stazhevsky et al. 1995), the pull-out resistance from suppressed dilation can reach the steel strength.

We have shown that this so-called sand anchor has increased bearing capacity with increased surface roughness of steel and borehole, and increased grain size, roughness and hardness. Filling and removing the granular material by air flushing is easy. Reversible anchors can similarly be placed into coarse- or fine-grained soil (Figure 13b). The borehole is preferably produced by penetration so that the surrounding soil is densified. Sand or gravel is screwed in by continuous flight auger, having the tendon inside the hollow auger. The granular material may be coarse like sand, is compacted and prestressed by the rotating auger, and works also as permanent drain. Suction and cementation can be achieved by fine-grained filling material if desired.

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