International Conferences on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics

1995 - Third International Conference on Recent Advances in Geotechnical Earthquake Engineering & Soil Dynamics

06 Apr 1995, 10:30 am - 12:30 pm

Dynamic Instability in Low-Cohesive Soils

E. A. Voznesensky
Moscow State University, Moscow, Russia

Proceedings: Third International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, April 2–7, 1995, Volume I, St. Louis, Missouri

Dynamic Instability in Low-Cohesive Soils

Paper No. 3.53

E.A. Voznesensky
Associate Professor of Geological Engineering, Moscow State University, Moscow, Russia

SYNOPSIS Dynamic behaviour of natural and model low-cohesive soils has been studied. All these silty-sandy soils demonstrated dynamic dilatancy with the exception of dense dry specimens and tended to liquefy if the degree of saturation $S_r > 0.9$. Beginning from the clay content about 1.5% by weight thixotropic hardening of low-cohesive soils can be registered and the relationship of this hardening versus normalized specific surface of the soils, calculated from BET equation, can be represented by a smooth S-shaped curve with three distinct parts characteristic for dilatant (cohesionless), dilatantlty-thixotropic (low-cohesive) and quasi-thixotropic (cohesive) soils.

INTRODUCTION

A small admixture of fines change dynamic response of clean sands and these dilatant soils may perform to some extent thixotropic properties. Such systems could conform silty sands, silts and loams. So there is a group of natural soils inter mediate between quasi-thixotropic cohesive and dilatant cohesionless ones which can be called low-cohesive soils. Their dynamic behaviour has some peculiarities: (a) very rapid strength degradation, (b) thixotropic strength regain after dynamic loading occurs against a background of poor compaction and progresses very slowly because of small clay content and low permeability; total duration of regain period varies from several hours to 1-2 days and the regained strength exceeds the initial one, (c) dynamic response is strongly moisture content dependent - both positive and negative dilatancy could occur, followed by liquefaction at the degree of saturation over a critical level, (d) extreme sensitivity to the vibrations with certain frequencies from 15 to 45 Hz, varying with moisture content and grain-size composition (Voznesensky et al. 1994).

Dilatantly-thixotropic behaviour of low-cohesive soils is a form of dynamic instability of soil sand rocks. But there are two major gaps in the framework of its understanding now: (1) grain-size boundaries of such soils are still obscure and (2) no quantitative criteria for identification of such systems exist. In this paper we try to solve these problems, basing on two main points.

1. Since thixotropic properties of soil depend primarily on physico-chemical activity of fines, which is, in turn, a function of their mineral composition - dynamic response and subsequent strength regain should be studied in terms of specific surface of the soil. Its value is an integrate characteristic parameter of soil structure and varies from almost zero to several hundreds square meters per gram of dry soil.

2. Dilatant and thixotropic effects should be measured separately. Here we assume them to be separated in time - thixotropic hardening begins after the end of soil compaction and pore pres sure dissipation. This is true only for non-saturated samples just at the end of dynamic loading. In saturated ones these processes partly overlap.

EXPERIMENT DESCRIPTION

A number of natural and model soils were used in experiments:

1. Clean quartz marine sand (Liubertsy quarries, Russia) - medium-grained, well-graded, $e_{max}=0.78$, $e_{min}=0.59$;

2. Alluvial silt (Fraser river, Vancouver, Canada). Plastic limit is 20%, liquid limit - 26.5%, specific gravity - 2.65 g/cm3. Mineral composition: andesine (56%), quartz (36%), hornblende (4%), clay minerals (4%): mixed-layer mineral (mica+montmorillonite), chlorite, illite;

3. Model soils - artificial mixtures of 92-98% clean quartz sand and 2-8% of Ca-montmorillonite particles (diameter less than 0.005 mm), extracted from natural bentonite clay.

Samples were prepared using moist tamping and pluviation (for saturated sand only) methods. For every soil series of samples from dry to saturated have been tested. The prepared specimens were stored in a high humidity environment for no less than 24 hours prior to testing. Also saturated silt specimens for dynamic triaxial experiments were cut out from the reconstituted sample prepared by consolidation of a slurry first in a cylindrical mould under one-dimensional conditions and then in the triaxial cell under isotropic or anisotropic conditions.

Soils were tested in a dynamic vane shear machine in Moscow University, Russia and saturated silt was also tested by dynamic triaxial apparatus in University of British Columbia, Canada.

Dynamic vane shear machine is described in detail by Voznesensky et al. (1994). Cylindrical 7 x 4 cm samples are tested to determine undrained strength (s) of the soil before, just after vibration and, using number of samples with the same moisture content, at any given time after vibration. So data for regain kinetics curves can be obtained. During the regain period specimens were also stored in a high humidity environment. Typical strength alterations of low-cohesive soil under dynamic loading and after it can be summarized by a curve presented in Fig.1.

It can be seen that 4 undrained strength values characterize this process: (1) initial (static) strength (s_0), (2) its minimum value - when the major part of structural bonds in the soil is broken (s_d) - this value is, however, uncertain and cannot be measured correctly,

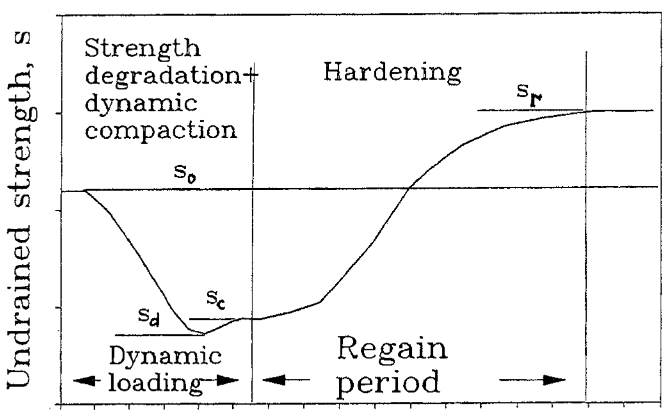

Fig.1 Kinetics of non-saturated low-cohesive soil strength degradation under dynamic loading and subsequent regain

since dynamic compaction of soil takes place against the background of structure degradation, (3) at the moment when dynamic compaction is finished (s_c), but no thixotropic regain has occured, and (4) maximum (regained) strength at the end of thixotropic hardening of the soil (s_r). Regain period for low-cohesive soils was found to vary from 5-10 to 18-20 hours. So in our experiments s_r value was determined 24 hours after dynamic loading. And we measured sc value just at the end of vibration for non-saturated samples, when pore pressuse could be considered u=0 and so dynamic compaction was assumed to finish. But this is not true for saturated samples and in this case s_c value also becomes uncertain.

Soils were tested in conditions of vertical harmonic excitation with frequency of 20 Hz, and the calculated dynamic deviatoric stresses varied from 12-14 to 36-40 kPa in one cycle of loading.

The UBC dynamic triaxial apparatus was described in detail by Vaid and Chern (1985). Saturated silt specimens 2.5" (6.4 cm) in diameter and 4.5-5" (11.4-12.7 cm) high were used in undrained stress-controlled tests with frequencies from 0.06 to 0.45 Hz and deviatoric stresses varying from 0 to 100-140 kPa. In several tests cyclic loading has been interrupted for 15 min to study the possibility of any thixotropic regain in 100% pore pressure conditions.

RESULTS AND DISCUSSION

Dynamic behaviour of natural soils

Clean sand tended to compact during vibration and thus to increase its strength. For loose (D_r about 30%) non-saturated samples in all the cases $s_c > s_0$ with maximum strength increase of 10% at the degree of saturation S_r=0.3-0.5. This is caused by the lubricative effect of pore water when capillary effects in soil are not pronounced yet. Saturated dense specimens (D_r > 90%) did not compact and samples tended to liquefy. It is due to undissipated pore pressure that s_c did not exceed the initial value and sometimes was even lower at the end of vibration.

In silt poor dynamic compaction (negative dilatancy) did not result in any strength increase at the end of loading and, on the contrary, some strength degradation ($s_c < s_0$) - up to 25% - was observed for the samples with S_r > 0.4. This very common behaviour for low-cohesive soils is due to the simultaneous occurence of negative dynamic dilatancy and thixotropic distortion of their coagulative structure.

Dynamic response of saturated silt in triaxial conditions after slightly anisotropic consolidation with σ'_{3c}=50 kPa and K_c=1.05 is presented in Fig.2. In both cases pore pressure built-up and axial strain development are very quick. These data also demonstrate that dynamic behaviour of low-cohesive soil is strongly influenced by the frequency of loading - rate of strain accumulation

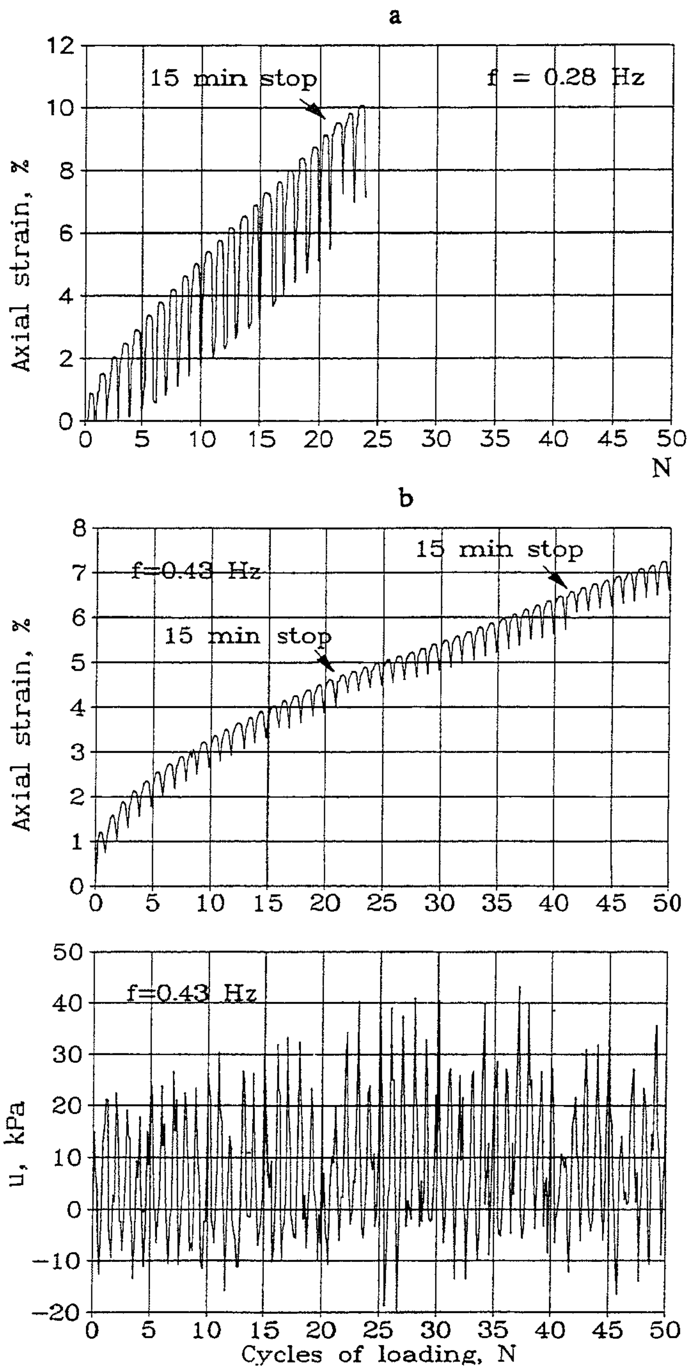

Fig.2 Dynamic undrained triaxial loading of silt

increases with the frequency decrease. E.g., in the 10th cycle axial strain was 5.3% in the case of loading with f=0.28 Hz and only 3.3% - with f=0.43 Hz, strain amplitude being 3.5% and 0.8% respectively. In the first case (Fig.2a) almost linear strain accumulation from the very beginning of loading is observed. We consider such effect of frequency to be caused by diffe rent relative duration of loading-unloading phases. The lower is the loading frequency, the longer are maximum dynamic stresses applied to the soil per every cycle. This explanation is true only for undrained conditions, since otherwise rate of pore pressure accumulation is strongly dependent on loading frequency and the discussed relationship may reverse.

Thixotropic effects in natural and model low-cohesive soils

Dynamic strength degradation of silt has a thixotropic nature: after 15 minutes break of loading (22nd cycle-Fig.2a, 21st and 42nd cycles-Fig.2b) strain amplitude decreased in half in the next cycle due to the thixotropic strength regain. Since this process occured in undrained conditions against the background of excessive pore pressure,compaction and thixotropic hardening of saturated soils could not be evaluated separately.

Thixotropic hardening of soils can be characterized by normalized parameter - strength regain ratio $SRR=s_r/s_c$. Thixotropic strength regain in silt is strongly influenced by the degree of soil saturation S_r. At low moisture contents ($S_r<0.5$) - when particle mobility is restricted - no thixotropic regain occurs and SRR÷1. In the interval of S_r from 0.5 to 0.9 a gentle increase of thixotropic hardening is observed (SRR changes gradually from 1.15 to 1.6). This is due to the facilitation of reorientation and repacking of particles with the increase of water content that a new coagulative structure with optimum energy arises as a result of this thixotropic regain. And in saturated silt (S_r÷1) a dramatic, but improper (as it was discussed earlier) increase of SRR over 2.5 is observed, caused by the total effect of simultaneous (at least partly) hardening and compaction of soil after dynamic loading.

TABLE 1. Specific Surface of Studied Soils

Group of soils	Soils	Specific surface, m^2/g
natural	quartz sand	0.2
	silt	16.4
model (quartz sand+ montmorillonite clay mixtures)	sand+clay 98%+2%	10.1
	96.5%+3.5%	15.6
	95%+5%	27.9
	92%+8%	37.9

Thixotropic potential of soils - an ability to strength regain is strongly dependent on their specific surface (F_s), which is considered here as an integrate parameter of soil and sensitive function of fines content and their physico-chemical activity. Specific surface (F_s) of all soils has been calculated from BET equation in modification by Aranovich (1991) using water vapour adsorption data over 50-65% sulphur acid solutions and results are presented in Table 1. Maximum SRR value for different natural and model soils, achieved by the end of regain period, versus their specific surface is presented in Fig.3 (for all specimens S_r is about 0.7).

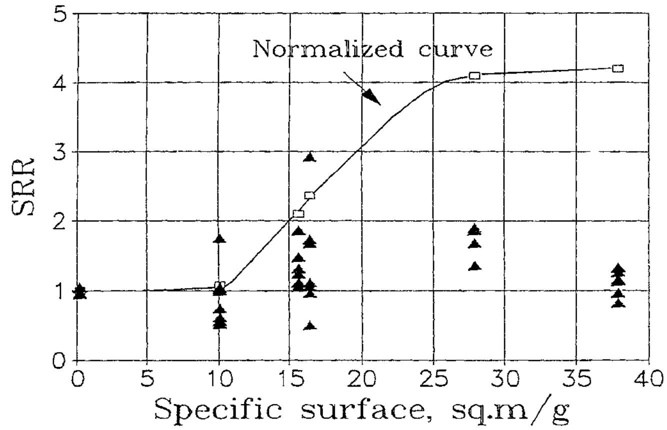

Fig.3 Thixotropic regain in studied soils

Clean sand (F_s=0.2 m^2/g) demonstrated no regain (SRR=1) that is quite natural for dilatant system. But at 2% clay content (F_s=10.1 m^2/g) SRR value is 1.17, then gradual increase of thixotropic potential (SRR=1.4-1.65) up to 5% clay content is observed, and then - its decrease (SRR=1.2) at 8% clay admixture. This is only an apparent effect since considerably different hydrophility of studied soils, determined exclusively by clay content, assumes diverse ratio of various kinds of adsorbed (especially, osmotic) water at the same moisture content. It means that in the soils with the same saturation degree the adsorbed water film thickness somewhat decreases with the increase of clay content, thus contributing to stronger particle interaction, and causes apparent decrease of soil thixotropic potential.

To eliminate this effect SRR values were normalized by soil hydrophility index $b_w=W_i/W_2\%$, where W_i - adsorbed water content of given natural or model soil under conditions of water vapour elasticity 0.629 at atmospheric pressure and $t^o=18^oC$, $W_2\%$ - adsorbed water content in the mixture with 2% of clay under the same conditions (W_i and $W_2\%$ can be obtained from adsorption isotherms). For studied soils b_w varied from 1.0 to 3.59. Normalized strength regain ratio $SRR_N=b_w*SRR$ versus specific surface F_s curve is presented in Fig.3. This S-shaped curve reflects relative thixotropic potential of low-cohesive soils. Its central steep part characterizes systems with F_s=10-30 m^2/g that are most sensitive to small changes in grain-size composition and should be called dilatantly-thixotropic soils. So, boundaries of this group are specified: soils with $F_s<10$ m^2/g have practically no thixotropic properties (SRR=1) and are dilatant systems, and only a gentle increase of thixotropic hardening is observed for soils with $F_s>30$ m^2/g. This thesis should, however, be verified experimentally for the systems with $F_s>>30$ m^2/g.

CONCLUSIONS

1. Dynamic response of low-cohesive soils includes negative dilatancy and thixotropic strength regain that can even occur against a background of excessive pore pressure.
2. Rate of dynamic strain accumulation in saturated low-cohesive soils is strongly influenced by the frequency of loading: in undrained conditions strain development intensifies with the decrease of frequency due to the longer application of maximum stresses per cycle.
3. The degree of thixotropic strength regain in low-cohesive soils is sensitive to specific surface variations, reflecting total effect of fines content and their physico-chemical activity. Soil hydrophility should be analysed with special attention since it controls interparticle forces and so, determines thixotropic hardening to great extent.
4. Low-cohesive soils with $F_s=10\div30$ m^2/g are most typical dilatantly-thixotropic systems.

REFERENCES

Aranovich, G.L. (1991), "New Polymolecular Adsorption Isotherm", J. Colloid Interface Science, 141: 30-43.

Vaid, Y.P. and Chern, J.C. (1985), "Cyclic and Monotonic undrained response of saturated sands", ASCE National Convention, Advances in the art of testing soils under cyclic loading session, Detroit, 120-147.

Voznesensky, E.A., Kalachev, V.Ya., Trofimov, V.T. and Kostomarova, V.V. (1994), "Dynamic Instability of Seasonally Thawing Silty Soils", Canadian Geotechnical Journal, 31, No.2 (in press).