PRECONSOLIDATION EFFECT IN NORMALLY CONSOLIDATED AGED CLAYS

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SUMMARY

This paper provides evidence from research and practice that most of natural normally consolidated clays are in fact preconsolidated due to aging. Examples of normally consolidated aged clays, including a clay investigated by the author at the site for the proposed Seaview Sewage Treatment Plant (New Zealand) are presented. Test procedures specifically designed to detect preconsolidation due to aging are described.

INTRODUCTION

A number of investigators have noticed that many clays and silts expected to be normally consolidated are shown by laboratory test results or field settlement monitoring data to be apparently preconsolidated. The laboratory tests on these clays and silts indicate a preconsolidation pressure (p_c) which is greater than present effective overburden pressure (p_o) in the ground at the level from which the samples are taken. Very often in addition to the laboratory consolidation test evidence, the field shear vane tests indicate undrained shear strength greater than would be expected from normally consolidated material.

It is very often assumed that only two mechanisms can cause preconsolidation (either erosion of the ground surface which have reduced overburden pressure, or variations of the groundwater level). In many cases the preconsolidation effect can not be explained by these traditional explanations. As utilisation of the preconsolidation effect often permits substantial cost savings in practical applications, the attention of many investigators around the world has been drawn to this phenomenon.

Until 1994 the author worked as an Associate Professor at the Chelyabinsk State Technical University in Russia and for 10 years was involved in large scale investigations of natural clays and silts. As a part of these investigations a new system for triaxial testing of soils was designed and constructed. Tests undertaken as part of an extensive investigation programme led the author to the conclusion that most of the natural normally consolidated clays are in fact preconsolidated due to aging. The author believes that the aging effect is of sufficient importance as to be taken into account in engineering design and practice.

EXAMPLES OF NORMALLY CONSOLIDATED AGED CLAYS

Leonards and his students first described this phenomenon of preconsolidation in apparently normally consolidated clay more than 30 years ago [8, 9]. They showed that normally consolidated soils can develop an apparent overconsolidation ratio of 1.4, simply by letting the clay age in secondary compression. After artificially sedimenting a clay and then letting it age for 200 days it was discovered that the clay had an overconsolidation Ratio (OCR) of 1.4 because of the ageing. Moreover Leonards noted that in his experience with natural clay deposits he had never encountered a supposedly normally consolidated clay that did not show some aging - preconsolidation effect.

Schmertmann [13] reviewing data of other writers noted that the soft Mississippi River delta clays around New Orleans and Baton Rouge, typically normally consolidated from a geologic view point, provide many examples of the aging - preconsolidation effect. Schmertmann refers to L Capozzoli who reported that he had many times successfully taken advantage in practice of overconsolidation caused by secondary consolidation to support structures over these clays, with only small observed settlement. Schmertmann reported experimental results showing the development of an apparent OCR equal to 1.5-2 for a normally consolidated Italian clay. Further he reported results showing the development of a 10% ageing preconsolidation effect in a clean uniform air-dry sand from Florida demonstrating that the age-strengthening effect can result not only from increased cohesion, but also from increased soil friction.

The most recent example is a silt encountered during geotechnical site investigations for the proposed Seaview Sewage Treatment Plan (New Zealand). In 1994, Beca Carter Hollings and Ferner Ltd was engaged by the Hutt City Council to investigate a number of sites in the Seaview area which were being considered as possible sites for a treatment plant. It was noted during those site investigations that silts at two sites adjacent to the Wellington Harbour and expected to be normally consolidated were indicated by test results to be apparently preconsolidated. The laboratory tests on the silt materials indicated preconsolidation pressures of approximately 200 KPa greater than effective overburden pressure in the ground at the level from which the samples were taken. In addition to the laboratory consolidation test evidence, the field shear vane tests indicated strength greater than would be expected from a normally consolidated material. The preconsolidation of the silts in this case could not be explained by any traditional explanation because geological evidence is that the silts have never had more than 3m greater overburden thickness than at present and have never been above the water table.

CAUSES OF OVERCONSOLIDATION IN CLAY

The most essential factors which bring a clay to overconsolidation state are as follows: (1) Secondary compression; (2) Geotechnical processes due to weathering; (3) Cold - welding of mineral contact points between particles; (4) Exchange of cations; (5) Precipitation of cementing agents; (6) Desiccation stress; (7) Mechanical aging resulting from increased basic soil friction, including dilatancy effects.

Secondary compression is a phenomenon where the void ratio decreases with time under a constant value of vertical stress. According to the concept proposed by Bjerrum [4], the additional structure developed by secondary compression increases linearly with increasing overburden pressure. Chemical bonding is a generalised term including cold welding of mineral contact points between particles; exchange of cations; cementation [3]. It is supposed that a bond structure is developed under constant value of the void ratio and the additional structure developed by chemical bonding is constant irrespective of the value of overburden pressure [7]. Desiccation is accompanied by an increase in internal effective stress and in turn a decrease in a void ratio.

The most interesting point of view has been presented by Schmertmann [13] who reported experimental results indicating that during aging of all soils (clays, silts and sands) the soil structure is densified by dispersive particle movements. Schmertmann gave many examples of aging improvement in soil engineering behaviour, both from the laboratory and the field, for short (from a few days to 100 years) and long aging times, and for clays, silts and even gravel. He tried to answer the question as to whether these improvements in soil behaviour result from an increase in the cohesive component of mobilised strength as a result of some form of cementation or internal bonding, as almost all references suggest, or from an increase in the frictional or mechanical component of strength. On the basis of experimental investigation, Schmertmann stated that age - strengthening effects result from increased basic soil friction, including dilatancy effects, and not from increased cohesion. The ageing mechanism includes grain slippage, soil - structure dispersion, increased interlocking, and postulated internal arching of stresses. According to Schmertmann the age - strengthening effect can develop relatively quickly because of the horizontal stress fluctuation.

TEST PROCEDURES

A great number of methods have been suggested to measure the preconsolidation pressure of normally consolidated clays. The simplest method is a conventional consolidation test using Casagrande's procedure to obtain the value of preconsolidation pressure. Frequently however, the e versus log p curve obtained in conventional oedometer test does not clearly distinguish preconsolidation. Therefore, other factors are examined.

For example, J E Bowles [5] states that the natural moisture content of the soil is one indicator of preconsolidation and if it is closer to the plastic limit than to the liquid limit the clay is almost certainly preconsolidated. R B Peck [11] and many others suggest assessment of the degree of preconsolidation using the Skempton's relation between undrained shear strength, plasticity index and overburden pressure. G Sallfors [12] suggests measuring pore pressure during a consolidation test in an oedometer. According to Sallfors the pore pressure is fairly constant during the early stage of the test. However, as the preconsolidation pressure is exceeded the pore pressure increases rather rapidly indicating a breakdown in the structure.

T Berre and L Bjerrum [2] proposed measuring preconsolidation pressure in the triaxial test. It is suggested that the specimens are consolidated under the insitu stresses for several days (so-called reconsolidation) and then compression test carried out. The authors indicated that the data obtained from drained triaxial compression test and a consolidation test carried out with no lateral deformation were very similar with respect to measured value of preconsolidation pressure. It was also noticed that preconsolidation pressure depended on the loading trajectory and was connected with critical shear stress - the maximum shear stress which can be mobilised under undrained conditions. The connection between preconsolidation pressure and critical shear stress noticed by Bjerrum was used by G Aas and others [1] to obtain a relationship among normalised field vane strength, plasticity index and overconsolidation ratio from oedometer test. The results obtained indicate that preconsolidation effect can be assessed from shear vane test data.

Large scale investigations of naturally and artificially aged clays were undertaken in the Chelyabinsk State Technical University (CSTU), Russia [10, 14]. A new system for triaxial testing of soils was designed and constructed for the investigations. This system comprises six working cells and a computer. The required air pressure in the cells is maintained and if necessary changed (according to the chosen test programme) automatically by an electronic pressure stabiliser. A sketch of the working cell is shown in Figure 1. The use of air allow the electronic strain transducers to be installed on the surface of a soil sample inside the working cell. Vertical and horizontal strain measurements are carried out in the central undisturbed part of the soil sample. The proposed strain measurement system makes it possible to avoid errors due to the higher compressibility of the thin disturbed soil layers adjoining the loading cap and the bottom platen. Stress in the piston 8 is measured by transducers 17 which are located inside the cell so as to avoid the influence of bush-friction on the measurement accuracy. The system allows deformations and loads to be measured with greater accuracy than in conventional triaxial tests. The electronic strain transducers were also used to measure deformation of soil samples in the modified oedometer (Figure 4a).

It was shown later [10] that preconsolidation pressure for aged clays can be assessed on the basis of the plate loading test data. If this data is available, then triaxial tests do not need to be performed.

TEST DATA

A great number of naturally and artificially aged normally consolidated clays were tested in the CSTU triaxial testing machine. It was noticed during the investigation that all remoulded specimens which were saturated with water and aged in odemeters under the vertical load of 40 kPa to 200 kPa for one to three years and all specimens of natural clays (without any exception) demonstrated preconsolidation effect. Preconsolidation pressures were found to be strongly affected by the duration of ageing (for artificially sedimented clays) and storage (for all clays and silts) when the soil samples were kept in the laboratory under an unstressed condition prior to testing. In addition to storage duration, for natural clays and silts preconsolidated pressure depended on the nature of soil and the geological history of the deposits.

It was shown [14] that a typical triaxial compression curve for an aged clay follow three stages (Figure 2a): a linear stage AB in which deformation is a result of the elastic deformation of particles without fracturing and breakdown of particle contact points; a stage BC in which deformation becomes plastic as a result of fracturing and breakdown of particle contact points, accompanied by sliding and locking of the degraded particles into a denser array; a stage CD of ultimate resistance and failure which can be described by the Mohr-Coulomb failure theory.

It was discovered that Poisson's ratio ν ($\nu = \varepsilon_3/\varepsilon_1$, where ε_3 - lateral deformation, ε_1 - axial deformation) increases as soon as stage BC starts (Figure 1b). The p and q (where $p = (\sigma_1+\sigma_3)/2$ $q = (\sigma_1 - \sigma_3)/2$, σ_1 – axial stress, σ_3 – lateral stress) corresponding to points A, B and C were plotted for several samples tested along different loading trajectories as co-ordinates defining a point in a stress space (Figure 3). The test data showed that the preconsolidated pressure varies depending on the type of a loading trajectory and very often is different from preconsolidation pressure Pc on the compression trajectory. All points representing elastic soil behaviour (stage AB) were found to be enclosed in the initial flow surface 2 which in fact consists of preconsolidation pressures measured on various loading trajectories.

The initial flow surface for aged clays was obtained in the form of a drop-shaped closed envelope. For slightly preconsolidated aged clays this surface does not contain the point O of no stress in all directions. Therefore, samples of the slightly preconsolidated clays experience plastic deformation as soon as they have been taken from an exploratory drill hole. These clays do not demonstrate a preconsolidation effect in laboratory testing unless they are tested immediately after sampling and consolidated at the same pressures as they carried in the field for 2-3 days prior to loading.

For heavily preconsolidated aged clays, point O is located inside the initial flow surface but the disturbance of the thin layers of soil adjoining the loading cap and the bottom platen makes it difficult to observe the

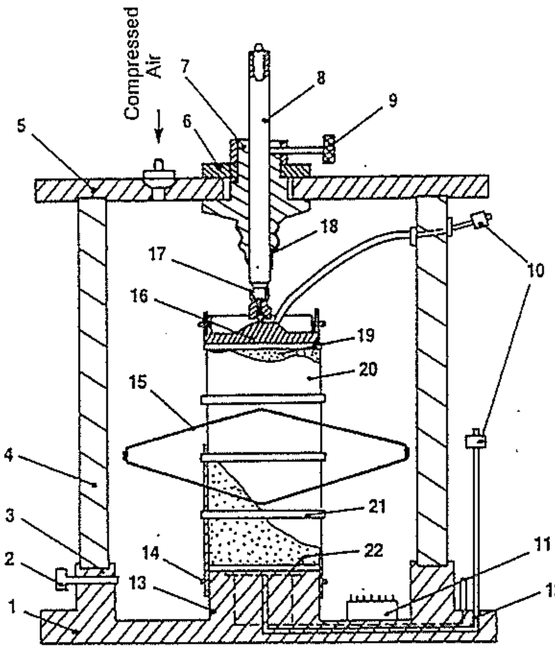

Fig.1 **CSTU triaxial testing machine**
1 - bottom platen; 2 - tensomanometer;
3 - gasket; 4 - cell; 5 - cover; 6 - nut;
7 - bush; 8 - piston; 9 - bolt; 10 - tap;
11 - connector; 12 - drainage; 13 - base;
14 - rubber ring; 15, 21 - strain transducers;
16 - loading cap; 18 - rubber insulator;
19 - sample; 20 - latex membrane;
22 - pore pressure transducer

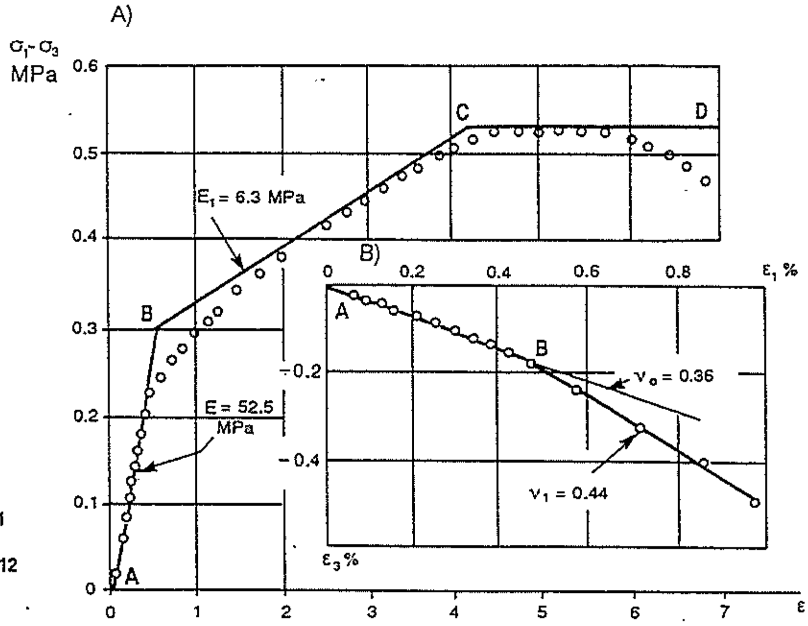

Fig.2 **Results of a drained test in CSTU triaxial testing machine**

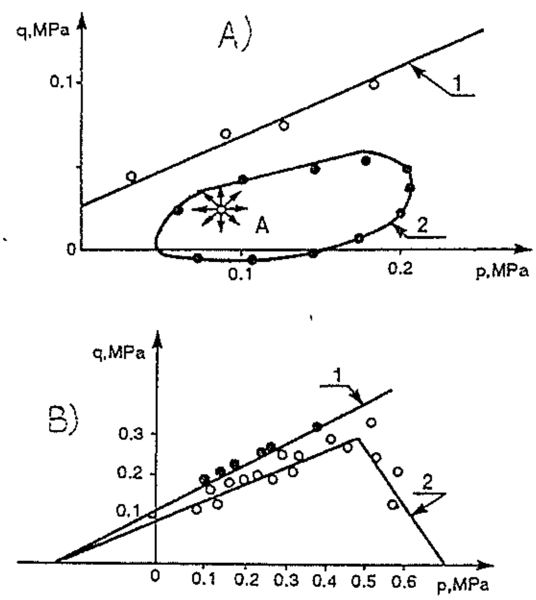

Fig.3 **Failure envelopes (1) and initial flow surfaces (2) observed in drained triaxial tests on slightly (a) and heavily (b) preconsolidated aged clays**

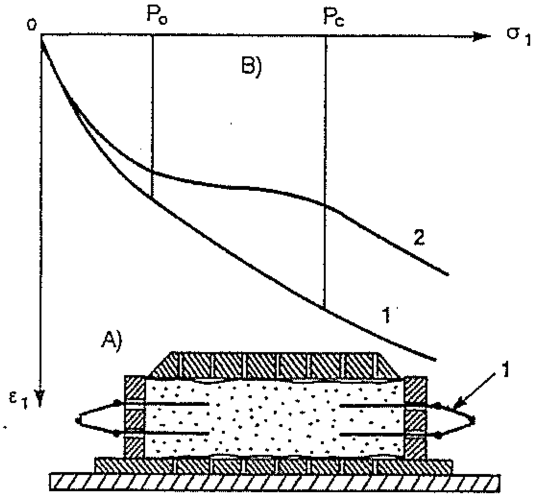

Fig.4 **Modified oedometer (a) with electronic strain transducers (1) and compression curves (b) observed in conventional oedometer (1) and modified oedometer (2) tests**

preconsolidation effect. The author compared conventional oedometer test data with that obtained in the modified oedometer shown on Figure 4a for 12 different aged clays. The preconsolidation effect was observed in all tests when vertical deformation was measured in the central undisturbed part of the samples. Two $\sigma_1 - \varepsilon_1$ curves shown on Figure 4b demonstrate typical conventional (curve 1) and modified (curve 2) oedometer test data.

SETTLEMENT PREDICTIONS

Foundation settlements can be predicted with a high degree of reliability if the subsoil consists of a normally consolidated or slightly preconsolidated saturated young clay. However, if the clay is preconsolidated due to ageing, the calculated settlements are likely to be more than real ones. R B Peck [11] states that even if the settlement prediction is based on the e - log p curves for undisturbed samples, the calculated settlements are likely to exceed the real ones and the amount of the discrepancy cannot be predicted reliably.

Lipends [10] compared field settlements of several buildings in the Boston area with the settlements calculated on the basis of the oedometer test data and found that the predicted settlements were four to five times the field settlement. Crawford and Burn [6] compared data in Canada and found that predicted settlements were 4 to 13 times the field settlement values. Russian building code specifies a number of correlations between the foundation settlement calculated on the basis of the oedometer test data and the real settlement. According to this code the calculated settlement can be 2 to 8 times the field settlement.

The author believes that the discrepancies between the field and the predicted settlements can be explained in terms of the preconsolidation effect. If the conventional tests fail to detect preconsolidation pressure and the clay is assessed to be a normally preconsolidated material, then the predicted settlements are much higher than the real ones. Normally, consolidated clays often occur in river valleys and on the margins of rivers and harbours. These areas are also often the sites of heavy tank structures (e.g. oil storage installations, sewage treatment plant tanks), flood banks and heavy breakwater bunds. In many cases preloading of such sites are undertaken to improve ground strength and reduce settlements, on the basis of assumptions of no preconsolidation. Where preconsolidation due to aging is taken into account and established by appropriate testing, considerable savings can be made.

CONCLUSIONS

1 Most of the normally consolidated natural clays and silts are preconsolidated due to ageing.

2 The nature of the aging is complex. The main factors affecting the aging effect are: secondary compression, desiccation stress, chemical bonding and mechanical aging. Mechanical aging is connected with fluctuation of horizontal stresses because of earthquakes and ground movement.

3. The preconsolidation pressure varies depending on the type of loading trajectory. In the stress space around the point corresponding to the insitu stresses there is to an initial flow surface containing a zone of elastic soils behaviour.

4 The parameters of preconsolidation can be assessed from modified triaxial and oedometer tests with high accuracy. The preconsolidation pressure can be approximately calculated from sheer vane test and plate loading test.

5 The preconsolidation effect influences the settlements of structures and must be taken into account.

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