SLURRY TRENCH WALL FOUNDATIONS

By

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Introduction

Hungarian soil conditions are not only favorable to, but even necessitate the wide-range use of slurry trench wall foundations and to develop a technology appropriate under Hungarian conditions. For little compressible load-bearing strata at variable depths under the earth surface, even by now, slurry trench wall foundations are superior to other types of foundation including precast piles. This is true especially if high bearing capacities are required. Trench work consisting of continuous soil exploration permits steady accommodation to soil conditions; trench depth can be varied according to the position of load-bearing stratum.

Slurry trench wall bearing capacity is a rather uncleared problem, especially the value and proportion of loads transferred by sides and bottom of slurry trench walls. In spite of the world-wide extension of this method, little has been published on its design; contractors abroad refrain from publishing slurry trench wall foundation calculations.

According to some observations, there is no difference between the bearing capacities of piles equal in size bored with a slurry or with casing.

Others state the soil to loosen around the slurry trench wall (Borus, 1969), likely to be injurious to the bearing capacity.

Anyhow, it can be stated that the behaviour of loaded slurry trench walls as well as the load bearing parameters are about the same as for piles, suggesting the bearing capacity analysis of slurry trench walls according to principles valid for piles (Petrasovits, 1971).

In conformity with its technology, the trench wall unit developed in the soil can absorb important forces on its surface due to friction. For calculating the vertical load bearing as for piles, knowledge of design skin friction coefficient is necessary (Kézdi 1958; Regele, 1968). One must know, however, if the mud cake adhered on the trench wall has a lubricating effect or not, and what is the friction coefficient to be assumed between the concrete and the mud-coated soil. This can be achieved by examining the slurry-soaken soil crust along the trench wall.

Slurry features

The slurry consists of *clay* dispersion in *water*. To improve and accelerate dispersion, and to improve the slurry, *admixtures* to increase weight, to control pH and viscosity are applied. Both technologically and economically it is advisable for the slurry to include few components. Many components both add to its cost, and oppose themselves to accommodate properties.

In trench wall making, soil and groundwater conditions are easy to determine, therefore slurry composition can be established as a function of soil properties, water table and chemical composition.

Slurry knowledge is now in development although safely applied in constructional practice for supporting trenches.

The slurry will only be adequate if dispersed clay does not precipitate after a longer rest, hence if it is stable, its viscosity exceeds that of water by as much as needed, and a given thixotropy is required.

Supporting effect only develops if the slurry forms an impervious membrane, a gelly, so-called "mud cake" on the trench wall.

Slurry is made with clean *water*, free of impurities damaging concrete. In conformity with practice and laboratory tests, water from wells, lakes, aqueducts is generally adequate for making slurry. Anyhow, before making important slurry quantities, it is advisable to make test mixes. If the slurry does not coagulate (does not become flocculant), then the water is appropriate. If in spite of coagulation, polluted water must be used, it has to be treated before using.

According to our tests, the *warmer* the water, the better it is for mixing.

Water *hardness* significantly affects slurry. Water of hardness degrees 10, 14, 30 or lower can be applied with bentonite F, with mine bentonite of Mád, and with colloidal bentonite, respectively, to obtain a stable dispersion.

Slurries are made with *bentonite* or sometimes *clay*, three types being:

slurry made of clay;

direct mine bentonite; and

processed bentonite.

Clay slurries are only advisable for trench making if proper clay is found near the site. Appropriateness of a clay for slurry making can only be stated after careful laboratory and field tests.

In Hungary, rich bentonite deposits are known to exist, suggesting their application from both technical and economical aspects.

Bentonite consists mainly of a clay mineral called *montmorillonite* responsible for its peculiarities. Montmorillonite crystals are latticed, each stratum being plane linked in itself. Compositions of some Hungarian and foreign bentonites are compiled in Table 1. The rather high scatter for the same bentonite type can be attributed to different determination methods (Buzágh-

Szepesi method, X-radiography etc.) According to American researchers McKinney and Gray (1963) slurries are the best if the bentonite consists of at least 85% of montmorillonite.

Table 1

Bentonite provenance	Montmorillonite percentage
Budatétény	57 to 90
Istenmezeje	40 to 85
Komlóska	30 to 64
Mád-Koldu	16 to 48
England	70 to 80
France	70 to 80
Germany	80 to 85
Italy	60 to 80
Wyoming	80 to 90

In addition to montmorillonite, bentonite may include other clay minerals (illite, kaolinite, glauconite), transformed rock residues (feldspar, mica, silica, tuff), new minerals formed in the deposite (pyrite, lime, gypsum, limonite), maybe remains of living organisms.

Most bentonite peculiarities may be ascribed to the *lamellar lattice* structure. Lamellae are visible under electron microscope. They may either be quite developed or finely floccular. Depending on whether the bentonite contains sodium, calcium or sometimes magnesium as exchangeable cation, Na-, Ca-, or Mg-bentonite are distinguished.

Na-bentonite alone is adequate for slurries; Ca-bentonite needs an activating agent to be used. *Activation* means the process of Ca-bentonite to become Na-bentonite upon cation exchange induced by certain chemical agents (soda, sodium hydroxide). Chemical transformation may be accelerated by heating. In practice the chemical agent is added in solid state to the material to be activated; although it would be more efficient as a solution, this would involve work excess.

The natural Na-bentonite and the activated Ca-bentonite are equivalent from nearly all essential aspects. Among Hungarian bentonites, those from Mád and Istenmezeje can be used in natural condition; F-bentonite and colloid bentonite are made by activation.

In slurry making, *soda* marketed in crystalline or dry form is mostly applied as an activating agent, primarily because of its efficiency and cheapness.

Slurry viscosity can be much increased by adding *carboxy-methyl-cellulose*

(CMC), little affecting its density and thixotropy. It is dissolved in lye, cold or warm water, depending on its preparation.

Dosage of *baryte* (of 4.2 Mp/cu.m density) may greatly increase the density of slurry but caution is recommended because it is injurious to the colloidal properties. Laboratory tests are needed to determine the dosage.

During trench making some water is released from the slurry to infiltrate the surrounding soil. Its quantity depends essentially on:

— the quality of bentonite in the slurry;
— the density of slurry;
— the time since the mud cake developed on the trench wall;
— the soil type surrounding the trench.

Laboratory tests demonstrated the water release to be lower for higher slurry densities (solids concentration), and subsequent to the mud cake formation.

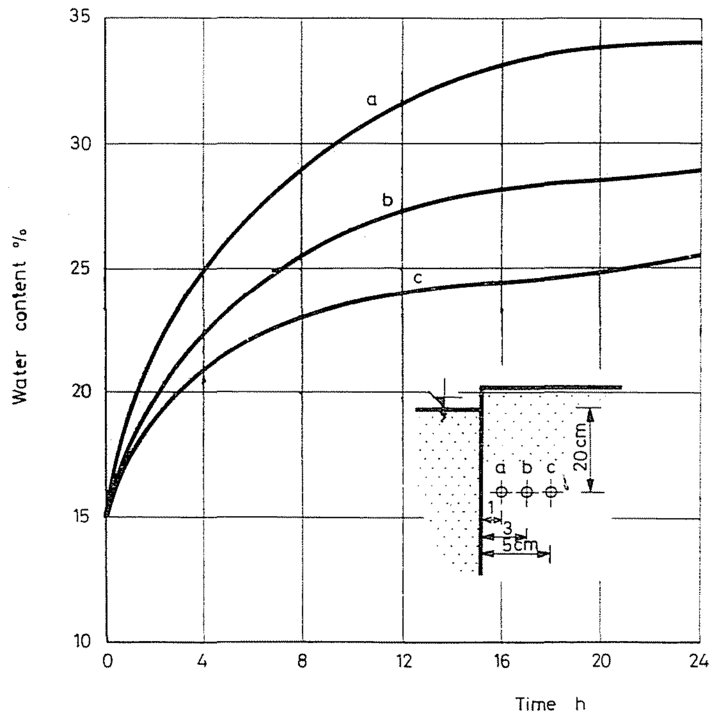

Fig. 1. Water content vs. time in Dunaújváros loess:

Sand	2%	$w_L = 24\%$
Sand flour	78%	$w_p = 19\%$
Silt	20%	$e = 0.52$

Water release by slurry in "transition soils" making up two thirds of Hungarian territory has been examined. Water content of a slurry of $\gamma_z = 1.04$ p/cm^3 density, made of F-bentonite, versus time has been determined at 20 cm depth below the soil surface, at points 1 cm, 3 cm and 5 cm away from the trench wall. The tested soil was Dunaújváros loess containing 2% of sand, 78% of sand flour, and 20% of silt, with a yield limit $w_L = 24\%$, a limit of plasticity $w_p = 19\%$, initial water content $w = 15\%$, void ratio $e = 0.52$. Results have been plotted in Fig. 1.

The water content in the soil is seen to have more than doubled in the contact zone, at a growth intensity decreasing with time.

Also water content variation with different densities of the given soil (loess) has been examined and plotted in Fig. 2.

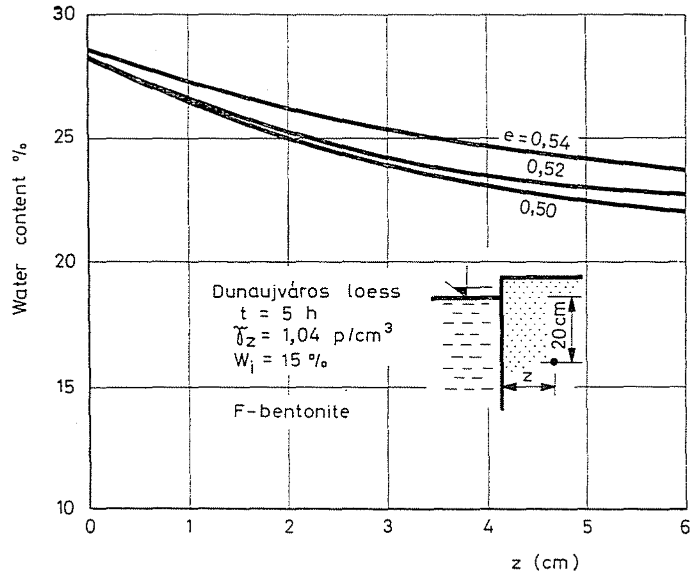

Fig. 2. Water content vs. distance from the trench wall, in soils of different densities

Water content variation in a rich clay vs. distance from sample edge spacing is shown in Fig. 3, the sample being 10 cm dia. immersed in a slurry of 1.06 p/cu.cm density, at a pressure of 2.1 kp/sq.cm. The clay being of low permeability, even after 24 hours, the water content is seen not to much increase except at the edge — in spite of the high pressure.

Slurry stability depends essentially on the bentonite quality (specific surface of particles), quantity (slurry density), pH value and mixing water quality.

Stability as a function of density of slurries made of bentonite F has been tested (Fig. 4). Slurries of a density of 1.04 p/cu.cm and over are seen to keep

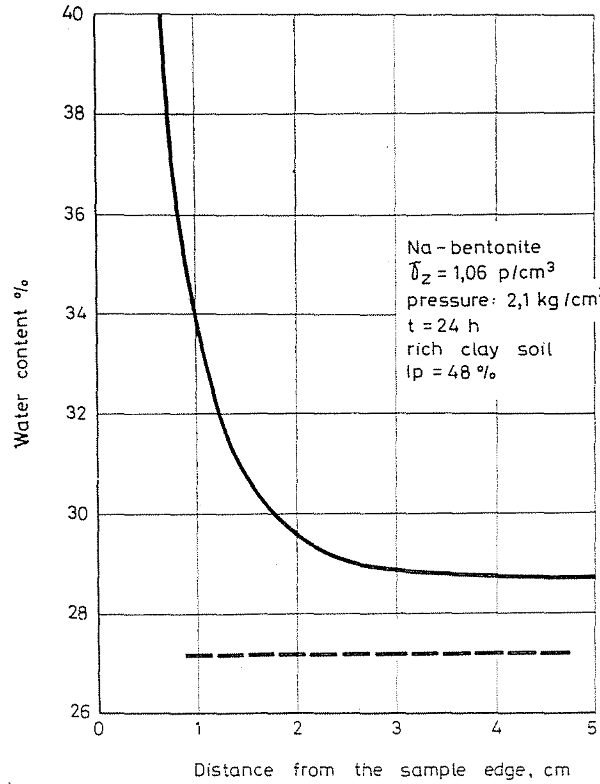

Fig. 3. Water content vs. distance from the sample edge

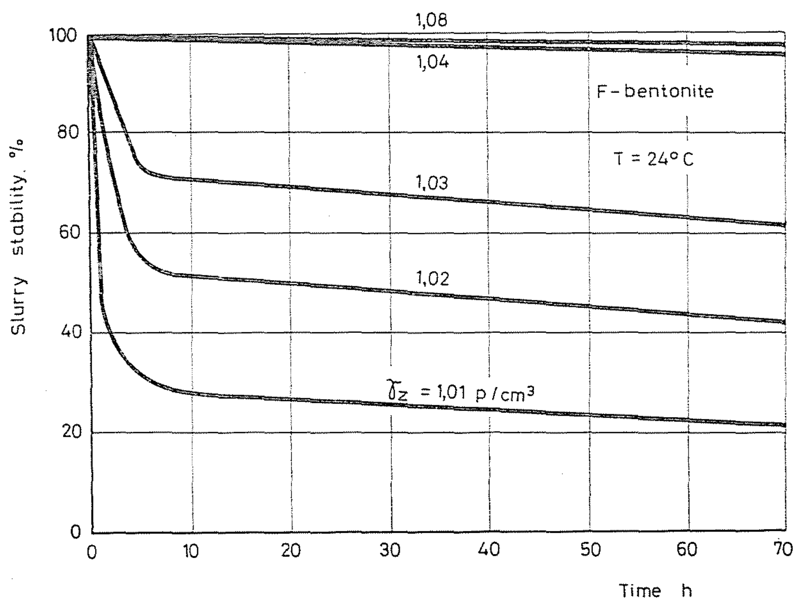

Fig. 4. Slurry stability vs. time in different soils

homogeneous at 24 °C even after 70 hours. Slurries below 1.04 p/cu.cm exhibited an intensive coagulation (water segregation) up to 5 hours after suspension has been made.

Irrespective of its density, the slurry may coagulate upon contacting ground water containing minerals — especially calcium — during trench making.

Rate of slurry penetration

Suspension introduced into the trench begins to diffuse, meanwhile on and near the trench wall surface, slurry solids gradually are filtered out. In the lateral surface an impervious, gelly mud cake is formed, inhibiting further oozing.

The rate of slurry penetration into the soil is definitely dependent on the grading of the supported soil.

SCHNEEBELI (1964) suggested the following approximate formula for the penetration depth:

$$1 = \frac{m}{\tau} \cdot \Delta p ,$$

where m a soil-dependent coefficient proportional to the nominal grain size;
τ slurry shear strength;
Δp difference between the slurry pressure and the pore water pressure in the soil.

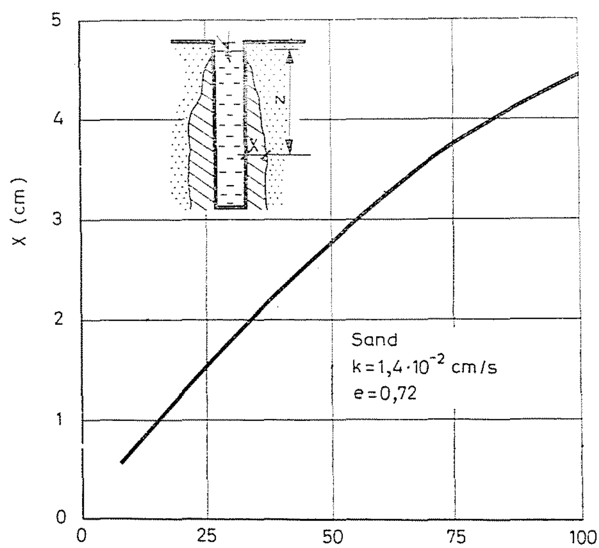

Fig. 5. Slurry penetration in sand soils

In *fine-grained* soils the penetration is of the mm order. During 24 hours, a slurry of a density $\gamma_z = 1.04$ p/m^3 penetrated by 6 to 7 mm a rich clay of plastic index $I_p = 48\%$ at a pressure of 3 kp/sq.cm.

Fig. 5 has been plotted according to our tests on slurry penetration into a soil of 4% gravel and 95% sand, a permability of $k = 1.4 \cdot 10^{-2}$ cm/s and void ratio $e = 0.72$.

In *coarse gravel, boulder*, the slurry penetration may exceed 1.5 m.

Shear strength of slurry-saturated soils

Some research workers state the soil stratum soaked with slurry has an increased shear strength. Slurry has been pumped out of a trench 3 m deep made in sandy gravel. Deprived of slurry, the trench kept its stability, while in the same soil no trench could be made without supporting. VEDER (1964) attributed this phenomenon to a certain increase of cohesion of the bentonite-impregnated soil. Gelification of the slurry infiltrating into the soil sticks grains together, increasing the shear strength of the soil. Also ELSON (1969) states the shear strength of granular soils soaked with slurry to grow somewhat. In Hungary, the first slurrying test was made in 1958/1959 at *Tát*, village near the Danube. Slurry has been pumped out of a ditch 13 m deep made in the sandy gravel, and the ditch remained stable for a while.

Other researchers state soaking along the trench surface to reduce the soil shear strength, practically irrelevant for the trench stability.

NASH (1963) immersed clay cylinders 3.8 cm dia. into bentonite suspensions of 6% and 8% for various times (4h and 8h). Triaxial tests showed the sample shear strength to much decrease; the greater the loss, the longer the immersion.

Thereafter the test was repeated on clay cylinders 10 cm dia. to show somewhat lesser shear strength losses.

Previous to making trench wall foundation proposed for an industrial plant, test slurrying has been made. After applying loading test on the test trench wall, the soil has been explored along the wall section. Undisturbed samples 40 mm dia. have been taken of the excavation, showing soil loosening along the trench, and shear strength loss in laboratory tests (BORUS, 1969). Samples taken at 3 cm, and at 25 cm from the trench exhibited uniaxial compressive strengths 45 to 60%, and about 40% lower, respectively, than those of samples taken from excavations before slurrying.

The above give a hint of two opposite concepts to exist in the international literature on the development of the shear strength of slurry-soaked soils.

To have an insight into the problem, several tests have been made at the laboratory of the Department of Geotechnique, Technical University, Budapest, on granular, transition and cohesive soils (FARKAS, 1972).

A direct rapid shear test has been applied to determine shear strength of granular and transition soils (using a box-type shear set made in Poland); while shear strength development of slurry-soaked cohesive soils has been examined in unconfined compression tests.

Each soil type has been tested saturated with slurries of densities $\gamma_z = 1.05$ p/cu.cm; 1.10 p/cu.m and 1.5 p/cu.cm and with water for sake of comparison.

The tested granular soil was *sandy gravel* of a uniformity coefficient $U = 3.3$.

Mildly soaking rather coarse-grained soils with slurry (40 cu.cm of slurry to 230 p of soil) caused a *shear strength gain* shown in Table 2. The more concentrated was the slurry, the higher the shear strength gain it caused. It was interesting to see both shear strength parameters (inner friction angle, cohesion) to increase.

Soaking the coarse-grained soil of equal physical characteristics with slurry (230 p soil with 80 cu.cm. slurry) displaced Coulomb failure lines representing the shear strength. In contrast to mildly saturated soil, in this case only cohesion increased, while the internal friction angle tended to decrease (see Table 2).

Table 2

Soil type	γ_z p/cm³	Φ°	c kp/cm²
Mildly saturated sand	1.00	37.2	0
	1.05	38.3	0.07
$s = 0.67$	1.10	38.6	0.12
$v = 0.33$	1.15	38.7	0.14
Strongly saturated sand	1.00	37.2	0
	1.05	33.5	0.08
$s = 0.67$	1.10	30.5	0.15
$v = 0.33$	1.15	27.0	0.23
Saturated transition soil	1.00	27.0	0.01
	1.05	17.0	0.01
(silty sand flour)	1.10	11.0	0.02
	1.15	9.5	0.11

The tested transition soil was a silty sand flour containing 14% of sand, 68% of sand flour, and 18% of *silt*. Mildly soaking the soil with slurries of different densities (245 p soil with 50 cu.cm. slurry), direct shear tests gave the results complied in Table 2. Increasing the slurry density, cohesion increased rather intensively like for strongly soaked granular soils while the internal friction angle tended to decrease.

In shear tests of slurry-soaked *cohesive soils*, cylinders 4 cm dia. and 6 cm high, trepaned from *medium clay* were immersed in slurry of a density $\gamma_z = 1{,}06$ p/cu.cm for various times (0 to 3 hours). The tested clay had an initial water content $w = 25\%$; void ratio $e = 0.86$; permeability coefficient $k = 5.10^{-8}$ cm/s. Unconfined compression tests on these samples coated by a gelly "mud cake" showed the longer the immersion time, the lower the compressive strength.

Laboratory test results have led to the conclusion that *coarse-grained soils mildly saturated with slurry exhibit somewhat increased shear strength* values. *Strongly saturated granular soils* though *acquire certain cohesion, to the expense,* however, *of internal friction angle.*

So-called "*transition*" soils also exhibit some cohesion increase upon bentonite impregnation, nevertheless the enhanced *loss* of internal friction angle entrains that of the *shear strength.*

The greatest is the shear strength loss for cohesive soils, attributable in part to the increased water content of the soil.

The above can be explained by the interaction between bentonite and soil. Their mixture may exhibit the prevalence of characteristics of either but this is not a simple function of quantity preponderance. High specific surface and activity to water of bentonite, as well as its extreme state change induced by water content provides for its greater influence, decisive for the development of shear strength characteristics.

Thus, an analogy can be demonstrated between the soil soaked with bentonitic slurry, and the "all-in" soil convenient for earth roads. Also the behaviour of mixed soils is decided by fines content. Below a limit coarse grain percentage, the greater grains are floating in the clay-water matrix (SEED, 1964; KÉZDI, 1967).

Particles in mildly slurry-saturated coarse-grained soils still *are in contact*, the relatively little bentonitic *slurry* in the voids *sticks them together.*

In much saturated coarse-grained soils and in fine soils, *solid particles* are in no contact any more but so to say they *are floating in the bentonite gel,* slurry properties prevail, at a shear strength loss.

Wall friction value

For the examination of wall friction, horizontal stresses along the enveloping surface of the trench wall have to be known. If a trench could be excavated without deforming the surrounding earth mass, then the enveloping surface would be acted upon by stresses due to the pressure at rest. These stresses are proportional to the depth. During excavation the soil grains along the wall are more or less disturbed, loosened, horizontal stresses decrease and an active ultimate condition may develop along the trench wall surface. The earth pressure coefficient drops below K_0, and because of the arching effect, stresses are not proportional to depth any more. It can be assumed, however, that horizontal stresses remain below the ultimate condition; deformations are less than plastic. Therefore in our case theoretical relationships of the laterally confined earth pressure are not valid.

VESIĆ (1963) tested the friction of vertical casing elements 5.7 by 31 cm in cross-section, in granular soils of various densities. Casing friction values vs. wall depth at soil failure are shown in Fig. 6 in sands with different porosi-

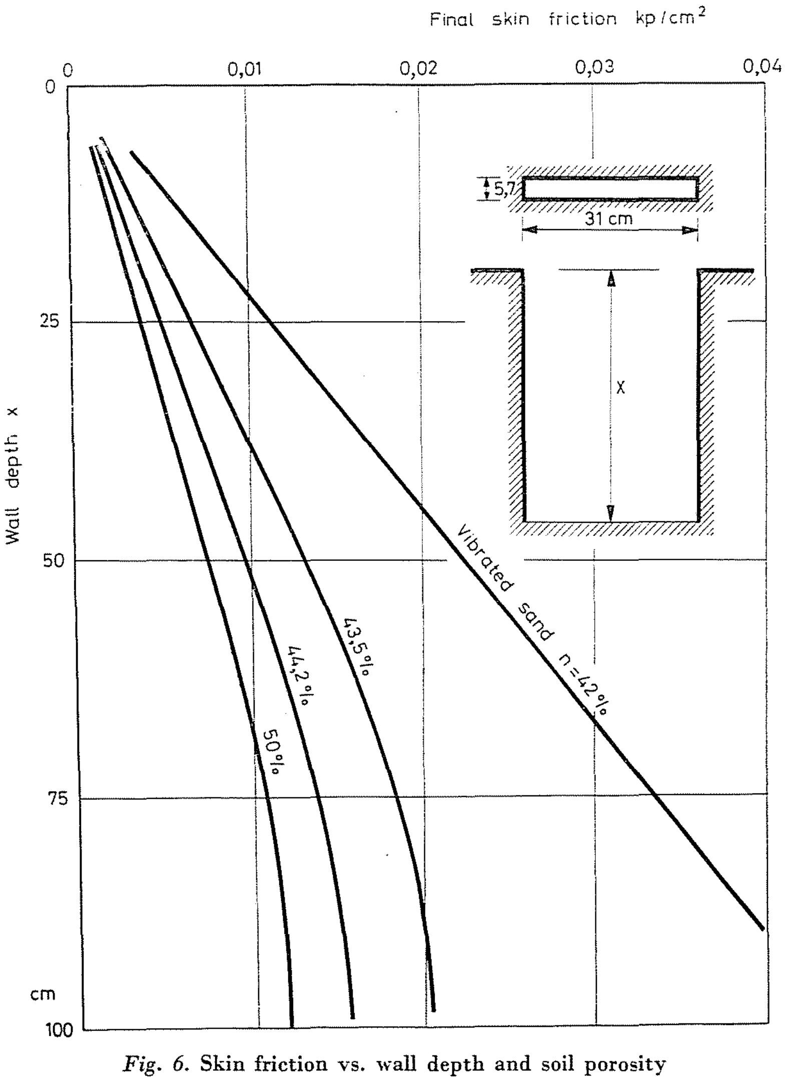

Fig. 6. **Skin friction vs. wall depth and soil porosity**

ties. Internationally published views on the effect of the mud cake adhering to the trench wall are rather divergent. Some assume important lubrication effects, to be reckoned with in casing friction. Others deny the lubrication effect.

Friction angles between concrete slab and water saturated sand and gravel have been tested with and without slurrying. Direct shear tests showed friction angle of 31.3° between soil and concrete to have dropped to 27.9° in presence of mud cake, hence, a friction coefficient loss of 9%. Internal friction angle of sand and gravel applied in our tests was 37°.

Accordingly, friction coefficient f_b between concrete and granular soil is about 80% that between soil particles (tg Φ):

$$f_b = 0.8 \cdot \mathrm{tg}\, \Phi;$$

while for gelly mud cake between wall and soil:

$$f_z = 0.7 \cdot \mathrm{tg}\, \Phi.$$

Also laboratory tests made abroad showed the bentonite cake to little reduce the wall friction.

Of course, large-size model tests are more reliable.

For instance, in England, driving resistances of piles 7 m long driven in the soil in normal conditions and surrounded by bentonite cake have been compared. Bentonite suspension was conducted to the casing by four tubes flanking the pile. Driving work was found to decrease by 30%.

Model tests were made with wooden piles 3 m long and 10.7 cm dia. to compare driving times of piles with and without bentonite paste coat. Bentonite proved to reduce driving time by 10 to 20%. 3 to 4 days after driving, no load bearing difference between both was found (BOYES, 1972).

Foundation works of the London headquarters of British Petroleum Ltd. comprised two concrete walls 0.5 m wide, 1.2 m long and 12.2 m deep (BURLAND 1963). One unit was constructed by the "dry" method — by means of a casing element — the other had its trench supported by bentonite slurry. According to the soil profile, the surface gravel bed 1.5 m thick was overlaying clay throughout.

Three weeks after concreting, load tests started in two cycles. In the first cycle, the load was increased by increments corresponding to one fourth of the calculated ultimate load bearing, up to one and a half times the ultimate load bearing. After any load increment, consolidation was awaited (until settlement was less than 0.05 mm during 30 min). Load diagrams of both units are seen in Fig. 7, demonstrating the unit made with slurry technology to settle more than did the "dry" unit.

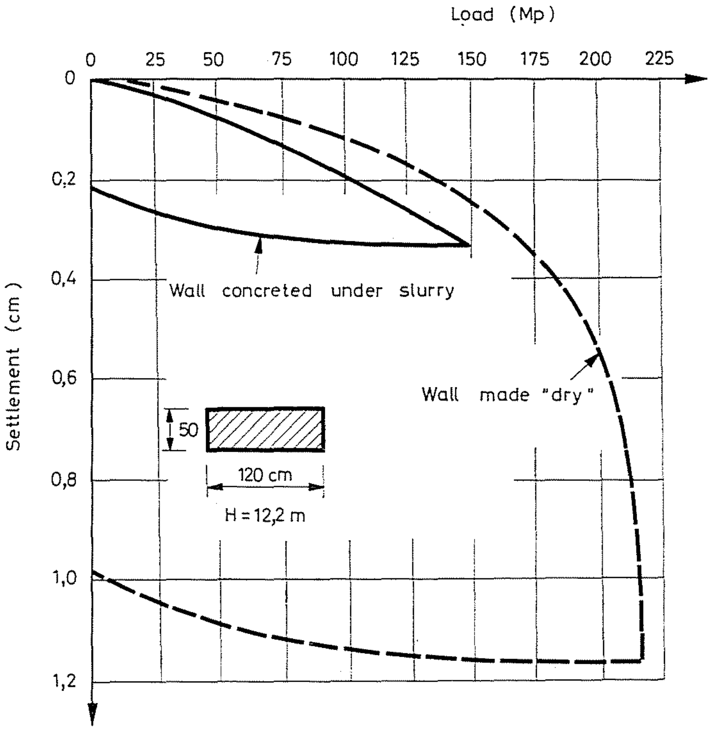

Fig. 7. Diagram of "stepwise" load tests of slurry trench walls

The second cycle consisted in loading at a constant settlement rate (0.63 mm/min) up to failure at about 340 Mp load bearing for both units.

Effect of the bentonitic mud cake to reduce friction is mostly examined in tensile tests. In Norway, four bored piles 24 cm dia. and 6 m long, have been made in clay soil, in identical circumstances (EIDE-AAS-JOSANG, 1972). In boring, the first hole was filled with water, the second one with slurry made of local clay, the third with Microsil slurry, and the fourth with bentonite slurry (baryte-admixed). Each slurry had a density of 1.25 Mp/cu.m. (Microsil consists of 97% SiO, 80% of the particles being below 2 μ, at a density of 2.22 Mp/cu.m.)

Pull-out test was made one and a half month after concreting, at a rate of 1 mm/min, excluding vacuum to develop under the piles.

After pulling out, piles made in water, in clay and Microsil slurry were seen to have hard clay crusts 1 to 5 cm thick adhered on the surface, due to the stabilizing effect of lime in the concrete. No such crust developed on the pile made in bentonite slurry.

The average surface friction of the first three piles agreed with shear strength values obtained with winged shear probe (3.1 Mp/sq.m) while the resistance was by 25% lower for the pile made in bentonite slurry.

Anchorage blocks for the suspended roof edge beams of the Munich Olympic Stadium were made in the slurry trench wall system. Before constructing, two test units with identical dimensions (0.6 m wide, 2.2 m long, 9 m deep) were built in the granular soil (Soos, 1972). In trench "A" the supporting bentonitic slurry has been left for two days, to leave the trench wall to be coated by a thicker mud cake than trench "B" immediately concreted. Pull-out test showed slurry trench wall unit to support much less tensile force than unit "B". The former exhibited an average skin friction of 4 Mp/sq.m for 25 cm displacement, the same values being 2.5 cm and 7 Mp/sq.m for the latter.

Summary

The properties of slurry consisting of bentonite dispersion in water primarily depend on its density and the bentonite quality. Our tests showed the slurry to need a density of at least 1.04 p/cu.m for a lasting stability. Slurry trench wall can only be made with Na-bentonite.

From slurry-supported trenches, slurry infiltrates the surrounding soil reducing its shear strength; the soil may even be loosened. Slurry infiltration in transition soils representing the majority of soils in this country is in general of the 10 cm order. Shear strength of the slurry saturated soil belt depends primarily on the impregnation degree, the slurry density, and the soil grain size. Strength loss is the greatest for cohesive soils.

Continuity of excavation, slurrying and concreting is of utmost importance; all operations for a given slurry trench wall should possibly be completed in 24 hours, in order to avoid a significant loosening of the surrounding soil, and an important gelly mud cake to develop on the trench wall.

In concreting, the gelly bentonite crust developed on the wall is though destroyed, nevertheless it persists between concrete and soil to act as a lubricant and affects load bearing. Laboratory and model tests show skin friction loss to be as high as 25 to 30%, to be considered in strength calculations. Available theoretical relationships are only informative approximations of the expected load capacity of slurry trench wall units. In this country, several load tests have been made on slurry trench walls of different forms, sizes, technologies, in different soil conditions, of a too low number, however, for a basis of comparison of load capacities; although field load tests have already yielded many valuable data.

Last but not least, no slurry trench walls meeting designers' load bearing requirements, and at the same time economical, can be made if not with a quite careful work, strict observation of technology rules, and conscious supervision.

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