THE COLLAPSE OF GYPSEOUS SILTS AND CLAYS OF LOW PLASTICITY IN ARID AND SEMIARID CLIMATES

ETUDE DU COLLAPSUS DES LIMONS ET ARGILES GYPSEUX DE BASSE PLASTICITE EN CLIMATS ARIDES ET SEMIARIDES

РАЗРУШЕНИЕ ЗАГИПСОВАННЫХ ИЛОВ И ГЛИН, ОБЛАДАЮЩИХ НИЗКОЙ ПЛАСТИЧНОСТЬЮ, В УСЛОВИЯХ СУХОГО И ПОЛУСУХОГО КЛИМАТА

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SYNOPSIS. A new failure mechanism has been added to the several already existing in gypsum: collapse. The soils indicated in the title of this paper constitute a continuous cause of trouble in hydraulic works or when there are changes in the water level, but not in other types of works and when the water table is deep.

INTRODUCTION

Gypsum affects to a 60% of the European part of Spain (Macau and Riba, 1962) and to many other countries (Justo, 1971 b), and causes continuous trouble owing to solution, erosion and attack to concrete.

Notwithstanding, there are many examples of successful foundations supported by gypsum, and some gypseous soils may be considered as excellent from many points of view (Mayer, 1962; Justo, 1971 b).

As a matter of fact, it seems that the kind of gypseous soil which has caused more trouble, specially in hydraulic works, is the one indicated in the title of this paper (Llamas, 1962; Klein, 1962). Because of this, a thorough research on this soil has been undertaken looking for other possible mechanisms of failure.

GEOLOGY

This paper refers mainly to one of the several kinds of gypseous materials existing in the Ebro Valley: the gypseous silts and clays derived from the weathering of saccharoid gypsum rock. They fill the bottom of depressions protected from the wind (fig. 1), and have been formed, in quaternary times, as colluvial or eolian soils. The frequent high gypsum content certifies one of these origins, because of the solubility of gypsum (Llamas, 1962).

A proof of the action of wind in the transport of some of these soils stands in their existence at long distances or at higher levels than the tertiary gypsum rock.

Some karst phenomena are present in these soils.

Fig. 1.- Gypseous soils from Aragón and gypsum rock hills. Cut at the front-left side

Their thickness increases from nil near the gypsum rock hills to 10 m. or more away of them.

INDEX PROPERTIES

Table I is a summary of these properties.

It has been shown by means of chemical tests that these soils are made out of gypsum, clay (specially kaolinite and illite) and carbonates.

Figure 2 shows an electron micrograph of the soil.

As a rule, the water content, the degree of saturation, the liquid limit and the plasticity index increase when the sulfate content decreases, owing to the high water retention capacity of clay.

Table I

Index tests and permeability

Water content (%)	5 - 25
Liquid limit	<38
Plastic limit	<26
Plasticity index	4 - 19
Degree of saturation (%)	24 - 64
Dry density (g/cm^3)	1,16-1,53
Void ratio	0,78-0,98
Specific gravity of solid particles	2,35-2,67
Coefficient of permeability (cm/s)	$5x10^{-6}$ - $4x10^{-4}$
SO_4Ca . 2 H_2O (%)	7 -100
CO_3Ca (%)	0 - 14
Casagrande´s classification of fine fraction ($<0,42$ mm)	CL or ML

Fig. 2. - Electron micrograph showing prismatic gypsum forms, kaolinite, etc..

The following aproximate relation has been found:

$$I_p = 14,6 - \frac{S}{9} \qquad (1)$$

where

I_p = plasticity index

S = gypsum content in percentage.

The water content is always below the plastic limit, and the degree of saturation is rather low, owing to the semiarid climate of the zones where it is found, and the deep water levels. A result of that is the high value of suction and the firm aspect of these soils in the absence of water (fig. 1).

The void ratio is of the same order of the one of loess, and indicates an open structure.

STRENGTH.

The unconfined compressive strength swings between 0,9 and 2 kp/cm^2 for a gypsum content less than 86%. When the gypsum content reaches this percentage the strength increases sharply (fig. 3). Failure is of a brittle type (v. table II), with appearance of vertical cracks.

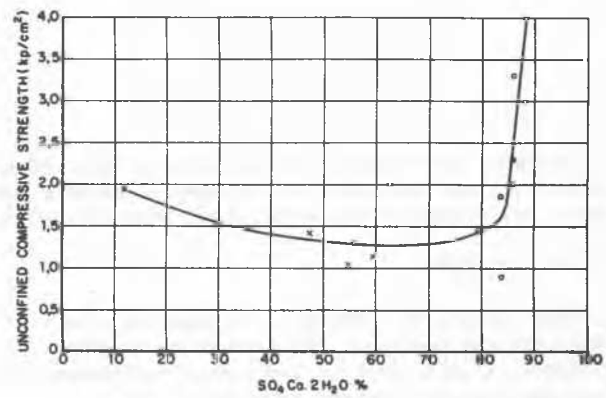

Fig. 3. - Relation between unconfined compressive strength and gypsum content.

The triaxial tests were carried out saturating the sample with a back pressure of 6 kp/cm^2.

After failure there are neither vertical cracks nor sliding planes, but the samples deform maintaining a cilindrical shape. In some samples clear signs of buckling were observed.

As indicated in table II, the effective angle of internal friction measured in undrained tests is lower than the one of drained tests. As the volume change at failure is usually nil in these tests, there is no energy correction to be made.

It is interesting to show the different stress-paths in both kind of tests (fig. 4). In the consolidated-undrained test the strong increase in pore-water pressure when the deviator stress increases produces a high decrease in σ_3' which leads to failure. On the other hand, in the drained test failure is produced by an increase in σ_1' with σ_3' constant.

That is the reason why the deformation at failure in the direction of σ_1' is much larger in the drained test (v. table II).

As a result, failure in consolidated-undrained tests is of a brittle type, with a sharp decrease in strength

Table II

Strength

		Average	Min.	Max.
Unconfined compressive strength (kp/cm^2)			0,9	4
Deformation at failure in unconfined compression (%)			2	5
Drained tests	c' (kp/cm^2)	0,10	0	0,30
	ϕ' (degrees)	29,7	23,6	34,6
	ε_f (%)		1,3	20
Consolidated-undrained tests:				
Criterion of $(\sigma_1 - \sigma_3)_{max}$	c' (kp/cm^2)	0,11	0	0,23
	ϕ' (degrees)	23,7	19,8	28
	ε_f (%)		0,7	3
Envelope of stress-paths	c' (kp/cm^2)	0,11	0	0,23
	ϕ' (degrees)	25,6	20,4	29,6
Constant water content test (one sample, 5 specimens)	c (kp/cm^2)	0,38		
	ϕ (degrees)	36 ($\sigma \leq 1,1\ kp/cm^2$)		

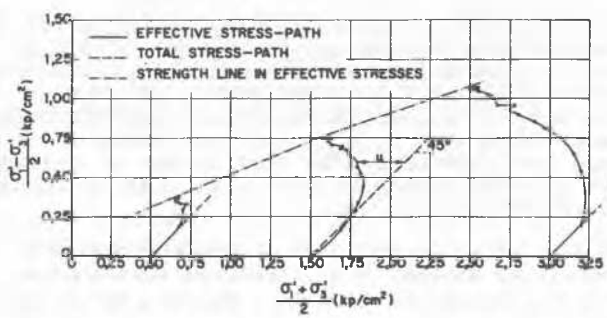

Fig. 4. - Stress-paths in consolidated-undrained tests.

after peak, produced, perhaps, by a collapse in the structure. This is, probably, the reason of the lower strength registered in these tests. Possibly, if the tests had been continued after the sharp decrease in strength, another peak, perhaps higher than the former, would have appeared.

As a rule, the larger the effective angle of internal friction the smaller the effective cohesion.

Figure 4 shows clearly the increase in pore pressure coefficient A when the deviator stress increases, and with increase in consolidation stress.

ϕ' increases with the sulphate content.

So as to investigate the nature of the unconfined compressive strength some samples were inmersed in distilled or in gypsum saturated water. As a rule, only samples with more than 86% gypsum resisted inmersion, although with a reduction in strength. So, it seems that in this soil gypsum acts as a stable cement only when it exceeds this percentage, although in other soils the vertical percentage is much smaller (Justo, 1971).

As the samples inmersed in distilled water did not behave worse than the samples inmersed in gypsum-saturated water, it must be deduced that capillary stresses have a predominant effect in the unconfined compressive strength (v. Dudley, 1970).

STRUCTURE AND PERMEABILITY.

The coefficient of permeability of these soils (previously saturated with a back pressure) is rather high (v. table I).

Figure 5 shows a microscope photograph of an undisturbed sample. In another micrograph a hole appeared that might help to explain the high permeabilities.

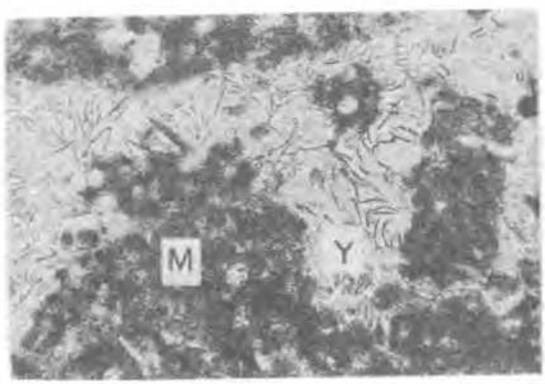

Fig. 5. - Microscope photograph of undisturbed sample, showing a brown basal mass (M), formed by clay minerals and carbonate microcristals, and gypsum filling cavities (Y) x 100.

In a special permeability test, a sample, saturated beforehand, was subjected to a continuous pass of water during two months. The permeability increased from 5×10^{-5} to 4×10^{-4} cm/s, and after the test the sample presented small longitudinal holes produced by the pass of water.

Owing to the saline environment, these soils exhibit a flocculated structure, with the probable existence of silt size peds (v. Barden, 1972).

COMPRESSIBILITY AND SWELLING.

Some data are summarized in table III.

Table III

Compressibility and swelling

Modulus of deformation in unconfined compression (kp/cm^2)	35 - 110
Modulus of deformation in plate loading tests with saturation (loading up to 2 kp/cm^2) (kp/cm^2)	14 - 62
$\Delta\sigma_1'/\Delta\varepsilon_1$ in consolidometer tests on saturated samples (loading up to 2 kp/cm^2) (kp/cm^2)	20 - 69
$\Delta\sigma_1'/\Delta\varepsilon_1$ in consolidometer tests with collapse (loading up to 2 kp/cm^2) (kp/cm^2)	15 - 66
Preconsolidation pressure of saturated samples (kp/cm^2)	1,3-2,1
Compression index of saturated samples	0,22-0,59
Swelling index of saturated samples	0,007 -0,020
Swelling under 0,1 kp/cm^2 (%)	0 - 0,3

Some tests were made in a special oedometer prepared so as to avoid the contact of the water of the sample with the atmosphere, similar to the one described by Yoshimi and Osterberg (1963). In this oedometer the change of water content was negligible.

The time dependent deformations, whether the samples are saturated or not are very important. The ratio between the deformations corresponding to one day and to 15 seconds after applying the load swings between 1,5 and 14 (fig. 6). Owing to the low degree of saturation of undisturbed samples, this retardation cannot be of a hydrodynamical type.

It is interesting to notice the very low values of the swelling index. In non saturated samples a swelling index of zero has been measured in two tests.

COLLAPSE

If we apply a load on a sample wait to the end of the settlements, and, then, flood the sample with distilled or gypsum saturated water an additional settlement occurs (fig. 7 and 8).

As in other cases of collapse the settlement curve will then join the one corresponding to a sample saturated from the beginning (fig. 8).

If we define a "coefficient of collapse" as the ratio between the settlement suffered by the sample when we add water (positive if compression and negative if it is swelling) and the total movement (considered always as positive), we find that this coefficient

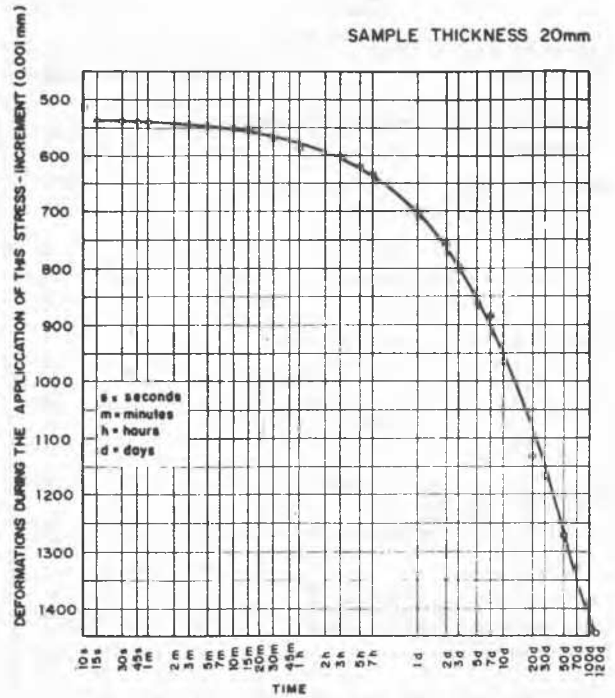

Fig. 6. - Time curves. Pressure interval 10 to 15 kp/cm^2. Natural water content.

varies from -1 for no loading and 0,78 for 3 kp/cm^2. This phenomenon is typical of soils with a low degree of saturation (v. Salas and Justo, 1971), and for that reason of arid or semiarid climates (v. Dudley, 1970). It is much more important in soils of open structure and low plasticity. The coefficient of collapse is much higher in this soil than in loess (v. Faraco, 1972).

In soils with no soluble salts all the settlement will occur upon flooding. But, if there are soluble salts, every time water is added there may be a new weakening of the structure causing a subsequent collapse.

PLATE LOADING TESTS.

Plate loading tests were carried out under saturation. In order to achieve this it was necessary to pour enormous quantities of water. Figure 9 compares the settlements obtained with the settlement of loess. It is easy to see that the gypseous soil is more compressible, although this is not revealed in laboratory tests (v. Faraco, 1972).

It is interesting to observe the large increase in settlement when we pass from 1 to 1,5 kp/cm^2. This phenomenon is not observed, at least with the same intensity in consolidometer tests.

The preconsolidation pressure obtained from samples saturated with gypsum water swung between 1,4 and -

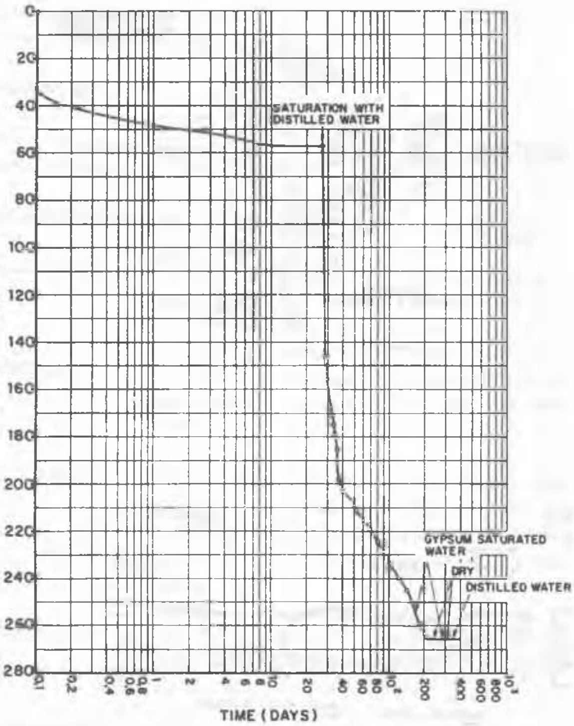

Fig. 7. - Collapse test; 98, 7% SO Ca . $2H_2O$; 3 kp/cm^2.

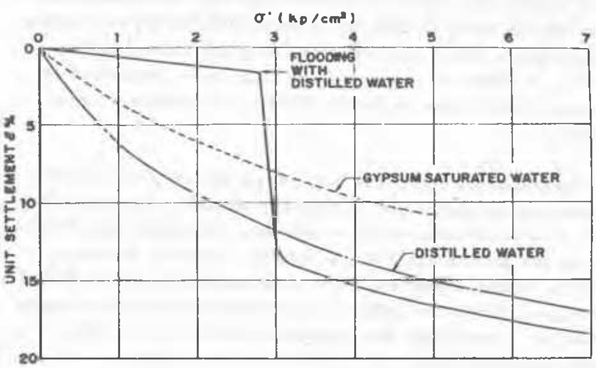

Fig. 8. - Settlement-pressure curve showing the effect of flooding the sample.

1, 8 kp/cm^2.

In any case, the shape of the curve is similar to the one of loess.

The importance of time-dependent settlements increa ses with loading. For 0, 5 kp/cm^2 nearly all the settlements occurred in less than one day, but for 2 kp/cm^2 the stabilization of settlements took 1, 5 months.

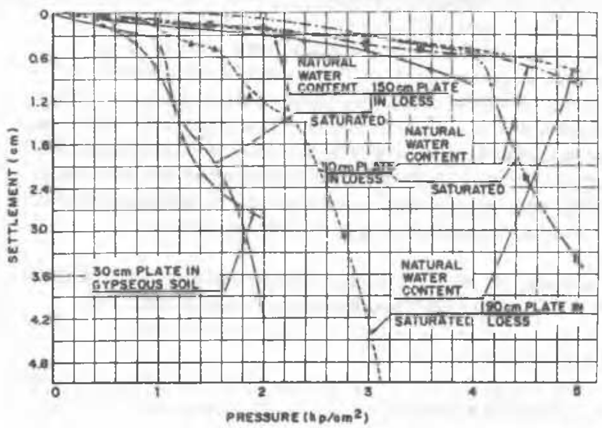

Fig. 9. - Plate loading tests in gypsum and loess. Loess curves reported by Gibbs and Holland (1960).

When the tests were ended, some vertical holes appea red in one of the pits. This may explain the high absor ption of water.

Owing to the importance of time dependent deforma - tions, in order to obtain the right order for the settlements of the plates, the modulus of deformation must not be obtained from routine consolidometer tests with one-day loading intervals, but from tests in which time enough has been spent in every interval (v. Justo, 1971 a and b).

BEHAVIOUR OF CONSTRUCTIONS FOUNDED ON THIS SOIL.

Settlement plates have been placed under a road em - bankment. Under less than 2, 80 m. height of embank- ment the settlements have been less than 1 cm. The road has not suffered any damage. Owing to the semia rid climate of Aragón, it is not probable that the increa se in the water content produced by the construction of the road will be enough to produce the collapse of the soil.

On the other hand, as it has been already stated, the behaviour of irrigation channels on this soil has been very troublesome, specially when the hydraulic gradient is high as in cut-and-fill sections (Llamas, 1962). The high coefficient of permeability, open structure and erosionability owing to the predominance of silt-size peds help to the deterioration of this soil.

As stated by Salas (1971) in some cases the caves may already exist in the soil (formed in geological times), and the action of the water from the channel may be to soften and collapse the roofs of the caves.

Another failure mechanism has been described by Romana and Soriano (1971).

One of the best observed accidents of this type happened in a suburb of Zaragoza during the first months of 1970. Suddenly a cave was produced with a depth of 6 m. and an aproximate diameter of 15 m. The escarpment was vertical, and only the central part of the roof collapsed. Three buildings affected by the caving in were demolished. No seepage from the surface existed in the neighbourhood.

A number of prior similar accidents are apparent in the same zone like the Barragan caves (fig. 10)

The soil profile is:

Topsoil (1 m.)

Cemented gravelly conglomerate (2 m.)

- Gipseous silty sands and gravels (4,5 m.)

- Clay and marl, (with gypsum).

Terrain is a near horizontal series of terraces sloping gently to the Ebro river. Phreatic levels have been often near the surface, so that the typical collapse caused by flooding is not possible.

Seasonal change of groundwater levels was usual in the zone due to winter rains and spring irrigations followed by a very dry summer. Actually the aquifer is being heavily pumped for the water supply to a recently developed industrial zone and levels are low in all seasons.

Gypsum concentration in water increases with decreasing distance to the river. There is a karstic-like process of gypsum dissolution by water. If there is no competent layer the cave structures fail when forming, giving way to a very gently sloping subsidence area.

If a hard layer is near the surface (as the conglomerate) then it forms a resistent roof to the dissolution caves, which collapse only when a critical size is reached, giving way to a doline form.

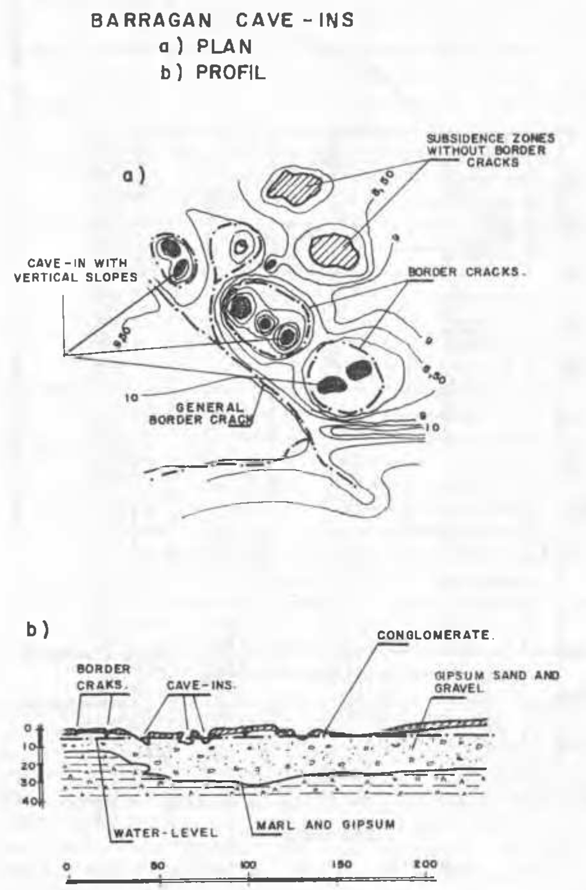

Fig. 10.- Cave-ins

The natural process is acelerated by over-exploitation of aquifers which increases effective pressures and trigger the collapse of a forming cave (Salas, 1971). A similar phenomenon has been observed in karstic limestone in South Africa (Jennings et al., 1965).

Compaction of the silts and clays of low plasticity produces an increase in the dry density and the effective angle of internal friction and an important decrease in the permeability (v. Justo, 1971 a ; Faraco, 1972). Some samples were compacted to a dry density higher than the natural one but less than maximun Proctor. Although the samples settled more than when undisturbed, the coefficient of collapse was much lower.

CONCLUSIONS

The gypseous soils of low plasticity are, in many respects, similar to loees, although they exhibit greater collapse and compressibility.

In hydraulic works, collapse, solubility and erosion may produce a quick deterioration of a channel.

On the other hand, in Aragón and when the water table is deep, it does not seem that the change in the water content produced by the sealing of the surface of the soil might bring it to collapse.

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