SETTLING BEHAVIOUR AND CLAY MINERALOGY

A. SRIDHARANⁱ⁾ and K. PRAKASHⁱⁱ⁾

ABSTRACT

Sedimentary soils are formed due to the process of settling of soil particles in suspension. The settling process is physico-chemical in nature as the soil contains chemically active clay minerals. The extent to which the clay mineralogy affects the settling process depends upon the initial water content of the soil-water suspension. For montmorillonitic soils, the limiting water content at which the nature of settling changes from a discrete free type to a flocculated free type increases with an increase in the soil plasticity and decreases with an increase in the soil plasticity for kaolinitic soils. While the diffuse double layer repulsion controls this kind of behaviour of montmorillonitic soils, the behaviour of kaolinitic soils can be attributed to the fabric effect.

Key words: clays, fabric/structure of soils, mineralogy, sedimentation (IGC: D2/D5)

INTRODUCTION

Settling is one of the important processes which lead to the formation of sedimentary soil deposits. Unlike studies on engineering properties like compressibility, shear strength and permeability of soils, studies concerned with the settling behaviour of soils are limited. Study of the settling behaviour of soils in the marine depositional environment with sophisticated instrumentation has lead Imai (1980) to identify four types of settling, namely:

- i) Dispersed free settling wherein the soil particles disperse and settle freely without mutual interactions.
- ii) Flocculated free settling wherein the soil flocs settle freely with no sharp interface formation between the settling soil flocs and the medium of settling.
- iii) Zone settling wherein soil flocs settle with strong mutual interactions among them, with the formation of a sharp interface between the settling soil mass and the medium of settling.
- iv) Consolidation settling wherein the soil mass settles en masse mainly due to consolidation.

Studies by Sridharan and Prakash (1997) have confirmed that these four types of settling can also occur in fresh water depositional environment. Of the aforementioned four types of settling, the first two deserve due attention on the following counts. Due to no mutual interactions among the settling soil particles, the dispersed free settling results in segregated sediments which are characterised by the presence of the coarsest particles at the bottom of the sediment and the finest particles at its top.

Flocculation results in mutual interactions among the soil particles and hence, will avoid segregation from occurring. In other words, the initiation of flocculation during the settling process is important in the formation of less segregated and more homogeneous sediments. In this context, the transition from dispersed free to flocculated free type of settling gains importance, as the engineering properties of the sediments like compressibility and permeability depend on the nature of the sediment formed.

Of the various factors affecting the settling behaviour of soils, the principal clay mineral type present in the soil can play an important role during the settling process. This is due to the fact that the two extreme type of clay minerals which can be present in the soils namely kaolinite (non-expanding lattice types of clay mineral) and montmorillonite (expanding lattice type of clay mineral) are responsible for quite opposing types of soil behaviour of soils with reference to properties like liquid limit and compressibility. While the liquid limit and compressibility of montmorillonitic soils are governed predominantly by the diffuse double layer related factors, those of kaolinitic soils are mainly controlled by the mode of particle arrangement as determined by the inter-particle forces (i.e., fabric) and the shear resistance at the particle level (Sridharan, 1991). The present note is an attempt to understand the effect of clay minerals on the settling behaviour of soils.

EXPERIMENTAL PROGRAMME

Six natural soils from different locations in Karnataka State, India and one commercial bentonite clay were used

ⁱ⁾ Professor of Civil Engineering, Department of Civil Engineering, Indian Institute of Science, Bangalore 560 012, India.

ⁱⁱ⁾ Assistant Professor, Department of Civil Engineering, Sri Jayachamarajendra College of Engineering, Mysore 570 006, India.
Manuscript was received for review on January 25, 1999.

Written discussions on this paper should be submitted before November 1, 2001 to the Japanese Geotechnical Society, Sugayama Bldg. 4F, Kanda Awaji-cho 2-23, Chiyoda-ku, Tokyo 101-0063, Japan. Upon request the closing date may be extended one month.

Table 1. Index properties of the soils used in the study of settling behaviour

No.	Soil	Liquid limit: %	Plastic limit: %	Plasticity index: %	Shrinkage limit: %	Grain size distribution: %			Principal clay mineral(s)
						clay size	silt size	sand size	
01	Bentonite	393.4	50.1	343.3	13.7	65.5	34.5	zero	Montmorillonite
02	Black cotton soil-1	100.8	51.9	48.9	13.2	70.0	28.1	01.9	Montmorillonite
03	Black cotton soil-2	76.6	35.4	41.2	09.9	55.0	32.6	12.4	Montmorillonite
04	Brown soil-1	64.6	26.6	38.0	14.5	40.0	41.6	18.4	Montmorillonite
05	Hemavathi project soil	58.5	31.0	27.5	19.2	20.8	51.2	28.0	Kaolinite
06	Kaolinite-1	48.0	35.6	12.4	35.9	10.0	75.0	15.0	Kaolinite
07	Red earth-1	38.6	18.0	20.6	14.7	39.5	23.5	37.0	Kaolinite

Note: The liquid limit values for all soils were obtained from Casagrande percussion method except for kaolinite-1 for which BS cone method was adopted.

in this study. The X-ray diffraction patterns of magnesium saturated, glycerol-solvated clay fractions of soils recorded with a SCINTAG X-ray diffractometer using $\text{CuK}\alpha$ radiation and nickel filter indicated that three soils are predominantly montmorillonitic, two are predominantly kaolinitic, one is montmorillonitic with traces of kaolinite and one contains kaolinite with traces of montmorillonite. The index properties of the soils are given in Table 1.

The experiments were carried out in glass jars of diameter 61.1 mm and 62 mm. The required quantity of oven dried soil was initially mixed with water to form a slurry and the water content was then increased to the desired value. The soil-water suspension was subjected to thorough mixing to ensure uniformity. The initial height of the soil-water suspension was maintained constant. In each case, the initial dry density of the soil-water suspension was varied over a wide range (i.e., 0.245 kN/m³ to 8.338 kN/m³). This resulted in a wide variation in the initial water content of the suspension, between a value as high as about 4000% and one as low as about 100%. The settling experiments were conducted in a fresh water environment with a pH of 7.2 ± 0.1 .

Each thoroughly mixed soil-water suspension was allowed to undergo settling. During the settling process, different modes of settling behaviour were observed. The heights of the sediments at various time intervals were measured with an accuracy of 0.5 mm.

RESULTS AND DISCUSSIONS

The following important observations were made during the settling process:

- When the initial water content of the soil-water suspension is very high, the soil particles settle freely to form the segregated sediments (i.e., dispersed free settling).
- When the initial water content of the soil-water suspension is below a certain value, the sediment formation line (i.e., the top surface of the sediment) moves up and vanishes after some time. After some more time, it reappears again at some height moving down-

wards with a cloudy suspension of relatively low intensity above, which diminishes quickly with time. (i.e., flocculated free settling).

With further reduction in the initial water content, zone settling as well as consolidation settling behaviours as observed by Imai (1980) in a marine settling environment were observed even in a fresh water settling environment. However, the present note concentrates on the study of dispersed free and flocculated free settling behaviours.

Figures 1–6 show settling curves indicating dispersed free settling and flocculated free settling for different soils used in this study except for bentonite. Bentonite, being a pure montmorillonite clay, took an extraordinarily long time for settling of more than 2 years. Hence, proper documentation of the variation of sediment heights with time could not be made. The study in the case of bentonite, hence, was restricted to the observation of modes of settling only. It has been mentioned above that for some duration during flocculated free settling, the top surface of the sediment (i.e., sediment formation line) is not visible. This period is indicated by dotted curves in Figs. 1–6.

The initial water content of the soil-water suspension has been taken as an index to represent the mode of settling behaviour exhibited by the soil-water suspension. The initial water content at which the type of settling changes from dispersed free to flocculated free is designated here as w^* . This limiting water content, w^* , has been observed to bear a definite relationship with the plasticity of the soil, the measure of which is taken as the plasticity index, I_p (Fig. 7). As can be observed from this figure, the trend of variation of w^* for kaolinitic soils is different from that of montmorillonitic soils. For kaolinitic soils, w^* decreases as I_p increases, whereas for montmorillonitic soils, w^* increases as I_p increases. This contradictory behaviour can be explained as indicated below.

Montmorillonitic soils contain a surface-active clay mineral named montmorillonite. For such soils, increasing plasticity indicates an increasing amount of montmorillonite in the clay content. Such soils, hence, re-

Fig. 1. Dispersed free and flocculated free settling curves for kaolinite-1

Fig. 4. Dispersed free and flocculated free settling curves for brown soil-1

Fig. 2. Dispersed free and flocculated free settling curves for red earth-1

Fig. 5. Dispersed free and flocculated free settling curves for black cotton soil-2

Fig. 3. Dispersed free and flocculated free settling curves for Hemavathi project soil

Fig. 6. Dispersed free and flocculated free settling curves for black cotton soil-1

quire extremely high initial water content to exhibit discrete free settling. As initial water content of the soil-water suspension reduces below a certain value w^* , the interaction among the diffuse double layer of the particles starts and hence, the soil particles can not settle freely as discrete particles. Instead, a group of particles exhibiting 'flocculation like' appearance due to the interaction among the diffuse double layers settle. At that

water content, the concentration of soil particles in the soil-water suspension is not high enough to initiate the interaction among the individual floc like formations. This is the reason why w^* increases as I_p increases for monmorillonitic soils.

The kaolinitic soils contain a relatively surface-inactive clay mineral named kaolinite. Kaolinites are more or less

Fig. 7. Relationship between w^* % and plasticity index Fig. 9. Relationship between w^* % and liquid limit

Fig. 8. Sediment formation curves illustrating opposite behaviour of montmorillonitic and kaolinitic soils

Fig. 10. Relationship between w^* % and activity

silt sized particles exhibiting lower plasticity. In other words, a kaolinitic soil with lower plasticity is expected to contain an appreciable amount of kaolinite clay mineral. The kaolinite clay mineral is known for its flocculant fabric and hence, the kaolinitic soils are governed by the fabric effect. Hence, a kaolinitic soil with lower plasticity flocculates even at a very high initial water content. As a result, w^* for such soils is expected to be higher. In kaolinitic soils, the increase in plasticity (i.e., I_p) is mainly because of the presence of other clay minerals, even though kaolinite is the dominant clay mineral. Due to the presence of other clay minerals, the flocculent nature of the soil fabric gets reduced and hence, there is a reduction in w^* with an increase in I_p .

Figure 8 shows the build up of the sediments of montmorillonitic and kaolinitic soils at constant initial water content of the soil-water suspension, which also cor-

responds to constant soil content in the suspension. In the case of montmorillonitic soils, as I_p increases, so does the height of the sediment formed. This can be attributed to increased diffuse double layer repulsion with the increase in plasticity of the soil which results in increased interparticle spacing. In the case of kaolinitic soils, the height of the sediment formed will increase with a reduction in I_p . This is due to the increased flocculation as a result of the presence of kaolinite clay mineral in its pure form in soils of lower I_p . However, it is to be noted that with more and more increase in the plasticity of kaolinitic soils, the height of the sediment formed can increase due to the presence of traces of expanding lattice type clay minerals.

Figures 9 and 10 illustrate the variation of w^* with the liquid limit of the soil and activity of the soil [activity = (I_p /% clay fraction)] respectively. As can be noted, unlike the w^* vs I_p relationships indicated in Fig. 7 for

montmorillonitic and kaolinitic soils, no such definite trends exist between w^* and either w_L or activity of the soil. This can be attributed to the following reasons:

- i) Liquid limit of a soil alone can not take care of the clay mineralogy.
- ii) Soil activity involves percent clay fraction which is an indication of only size of the soil particles and not the clay mineralogy.

CONCLUSIONS

Important conclusions drawn from the present study are indicated below:

- 1) The limiting water content, w^* , at which the nature of settling changes from discrete free type to flocculated free type is a function of the dominant clay mineral present in the fine grained soils.
- 2) For montmorillonitic soils, w^* increases with the plasticity. This can be attributed to increasing double layer repulsion with the increase in plasticity of montmorillonitic soils.

- 3) For kaolinitic soils, w^* decreases as the plasticity increases. This can be attributed to the fabric effect.

As the settling can be regarded as the volume change process, the above conclusions reinforce the earlier findings that the volume change behaviour of montmorillonitic soils is governed primarily by the diffuse double layer repulsion and that the volume change behaviour of kaolinitic soils is mainly controlled by the shearing resistance at the particle level which in turn depends upon the mode of particle arrangement (i.e., fabric) (Sridharan 1991).

REFERENCES

- 1) Imai, G. (1980): Settling behaviour of clay suspension, *Soils and Foundations*, **20** (2), 61-77.
- 2) Sridharan, A. (1991): Engineering behaviour of fine grained soils—A fundamental approach, *Indian Geotech. J.*, **21** (2), 133-144.
- 3) Sridharan, A. and Prakash, K. (1997): Settling behaviour of fine grained soils, *Indian Geotech. J.*, **27** (3), 278-309.