Diagenetic Effects on the Density of Argillaceous Sediments During Compaction

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(With 12 Figures and 1 Table)

Abstract

Based on data from various regions, the depth dependency of the density of sedimentary layers of the lower and higher sedimentation rates such as for deep ocean floor and oil field in large-scale sedimentary basins, respectively, was studied. A clear relationship was found to exist between the density gradient and the sedimentation rate. To clarify the geological significance of this observed relationship, a simple model for the compaction process is proposed. The fundamental equation is expressed as

\[ e_t = e_{oj} - C_{ci} \log P - C_{ac} \log t \]

where \( e_t \) is void ratio of a layer under effective pressure \( P \) and elapsed time of secondary consolidation \( t \), respectively, and \( e_{oj} \) is void ratio under a specified condition, \( P_o \) and \( t_o \). The constants \( C_{ci} \) and \( C_{ac} \) are the compression index and the coefficient of secondary consolidation, respectively.

The results of theoretical analyses showed good agreement with the actual density-depth relation over the wide range of depth. In addition, most of the observed data plot on or near the theoretical line on the diagram showing the relationship between density gradient and sedimentation rate. The data from the trench axis in the Nankai Trough, however, deviate significantly towards the over-consolidation area from the standard line on the diagram. This supports the idea that the accretionary prism at the convergent plate margin has not only undergone gravity consolidation but also obvious tectonic consolidation.

Erosion of the strata also influences the original nature of the density distribution with depth. The thickness of eroded strata was estimated to be 150 meters in the Akita oil field region and over 550 meters in the Kwanto sedimentary basin, which is known as the biggest Quaternary basin in Japan.

Key Words: Density, Void Ratio, Compaction Model, Daigenesis, Secondary Consolidation, Aging.

1. Introduction

Density is the most fundamental quantity among various kinds of physical properties. Many physical and mechanical properties of sediments strongly depend on the density or the void ratio.

The study of porosity changes in argillaceous sediments has been made by many authors since Steno’s grand works in the seventeenth century. RIEKE and CHILINGARIAN (1974) and CHILINGARIAN and WORF (1975, 1976) have broadly reviewed an enormous
amount of studies concerning the compaction of various kinds of sedimentary rocks.

Since the 1960's, many measurements of bulk densities of drill-core samples have been made at exploration oil fields. The spatial density structure has been revealed by much data in the oil fields. The characteristics of density distribution have been shown to be strongly affected by geological structures such as the unconformity or the fault (e.g., MATSUZAWA, 1961, 1962, MIYAZAKI, 1966).

Although considerable effort has been concentrated on the search for a best fitting function between the density and depth, the physical meaning has yet to be revealed clearly.

2. The factors influencing the physical property of argillaceous sediments

The cohesive geo-materials have been undergoing remarkable changes in their physical properties and structural fabrics during various kinds of geological processes. As these changing processes closely correspond to the physical and physico-chemical processes called diagenesis, the investigation of the changing processes in the physical properties of sediments is also considered to be important to explain the mechanisms of diagenesis.

The theory of the diffuse double layer in colloid chemistry has been introduced into the clay-water-electrolyte system and applied to soil behavior with some success. MITCHELL (1976) has broadly reviewed physical and physico-chemical processes in the soil from the standpoint of soil mechanics, and he has given a consistent explanation about the surrounding topics and applications to geotechnical problems.

The density of argillaceous sediments is thought to depend on numerous factors,
including lithology, grain size, sedimentation rate, wave loading, electro-chemical property of pore water, geologic age and erosion (Fig. 1). Quantitative study of these factors, however, has not been adequately made, and a study of the processes leading to changing density, based on microscopic structure under geological conditions, has yet to be made.

3. The relation between density and depth

RIEKE and CHILINGARIAN (1974) and PERRIER and QUIBLIER (1974) compiled the relation between the observed porosity of mudstone and its burial depth, using mainly the bulk densities of specimens sampled from some basinal areas such as the oil field. Fig. 2 shows, as one of the examples, the relationship between porosity and depth for argillaceous sediments. There is a relation between the porosity $\phi$ and the wet bulk density $\rho$ as follows

$$\rho = (1-\phi)\rho_s + \phi\rho_w \tag{1}$$

where $\rho_s$ and $\rho_w$ are the density of grain and water, respectively. The general trend of the porosity change indicates that its ratio to depth decreases with depth. Further,
the lines indicating the porosity versus depth relation are significantly scattered as seen in Fig. 2. These lines tend to converge in the high-porosity zone, that is, the depth/porosity range becomes wider with decreasing porosity and narrower with increasing porosity.

To examine the time dependency of the compaction of sediments, we have collected data of the density distributions associated with reliable chronological information for the sediments. Six samples are from sedimentary basins, namely: the Osaka Basin, OD-1 (Osaka City, 1964); Osaka Basin, OD-2 (Osaka City, 1965); Akita Basin (MIYAZAKI, 1966); Niigata Basin (MATSUZAWA, 1961, 1962); Kwanto Basin (Nirei et al., 1972); and Po Valley (SKEMPTON, 1969; STARE, 1959; ROCCO and JABOIL, 1959). Five samples are from DSDP Sites which were drilled by Deep Sea Drilling Project, namely: the DSDP Site 527, L.74 (RABINOWITZ and BORELLA, 1984); DSDP Site 357, L.39 (PERCH-NIELSEN and SUPCO et al., 1977); DSDP Site 594, L.67 (FAAS, 1982); DSDP Site 474, L.64 (CURRAY and MOORE et al., 1972); DSDP Site 298, L.31 (BUMA and MOORE, 1975).

These locations are shown in Fig. 3. We did not use the data from the strata containing predominantly limestone beds or diatomaceous ooze because the compaction characteristics of calcareous or diatomaceous sediments are somewhat different from ordinary sediments (McCrossan, 1961; Hamilton, 1960, 1976). The density distribution with depth at each site is expressed as a single line in Fig. 4 by averaging and smoothing the original data. As shown in Fig. 4, the curves showing those variations with depth have a similar tendency to those seen in Fig. 2 if porosity is replaced by density. This tendency seems to represent the presumable compaction process of argillaceous sediments in the common sedimentation fields.

4. Theoretical model of density variation with depth

Figs. 2 and 4 indicate that the density versus depth curve varies at each site and that their curves tend to converge at near the ground surface.

In order to discuss density changes under the geological conditions, it is necessary to introduce a simple consolidation model. As a stratum generally consists of a set of the single-layers, we can assume that the void ratio of i-th layer \( e_i \), is expressed by a function of the effective overburden pressure \( P \) at the normal consolidation stage, namely:

\[
e_i = e_{0i} - C_i \log \left( \frac{P}{P_o} \right)
\]

where \( e_{0i} \) is the void ratio at effective overburden pressure \( P_o \), and \( C_i \) is a constant named as compression index which depends on such factors as lithology, grain size and soil consistency. Let \( V_{si} \) be an equivalent thickness of the solid part of the i-th layer. Then the bulk thickness of i-th layer under effective overburden pressure \( P \), is

\[
V_i = V_{si}(1 + e_i)
\]

where \( e_i = e_{0i} - C_i \log \left( \frac{P}{P_o} \right) \). Consequently, the thickness of whole strata is
Fig. 3 Locality map of the deep drilling sites from which data relating to density variation with depth is cited in this study. A: Akita Basin, B: Lake Biwa, K: Kwanto Basin, N: Niigata Basin, O: Osaka Basin, P: Po Valley, T: Nankai Trough (Site No 298), Number is the Site No. of DSDP.
The void ratio of the whole strata can be expressed as

\[ e = (\Sigma V_s / \Sigma V_{si}) - 1 \]  

(5)

If a stratum exists at sufficiently great depth so that the effective pressure can be regarded as constant in a stratum, we have

\[ e = \Sigma V_s e_s / \Sigma V_{si} = (\Sigma V_s C_c / \Sigma V_{si}) \log (P/P_o) - e_o - C_c \log (P/P_o) \]  

(6)

where \( e_o \) is a bulk void ratio of the strata under effective pressure \( P_o \) and is equal to \((\Sigma V_s e_o / \Sigma V_{si})\). Furthermore,

\[ C_c = \Sigma V_s C_c / \Sigma V_{si} \]  

(7)

Therefore, the index \( C_c \) is found to be the weighted average for a set of layers as proportional to the thickness of solid part in each layer.

The above equation (6), however, should be valid in a special case, namely, at some
constant time after the termination of the primary consolidation. Hence, the variation of void ratio with time under a constant effective pressure can be expressed as

$$e_i(t) = e_{oi} - C_{ci} \log \left( \frac{t}{t_0} \right)$$

(8)

where $C_{ci}$ is a constant called the coefficient of secondary consolidation, which exhibits the degree of elapsed time-effect on the consolidation.

Consequently, the void ratio at elapsed time $t$ under a condition of constant pressure $p$ in the case of a single layer may be given by combining the equations (6) and (8), as follows,

$$e_i = e_{oi} - C_{ci} \log \left( \frac{P/P_o}{C_{ci}} \right) - C_{ci} \log \left( \frac{t}{t_0} \right)$$

(9)

When applying the above equation to the whole strata, the subscript $i$ in the equation should be removed wherever it occurs. Namely,

$$e = e_o - C_{a} \log \left( \frac{P/P_o}{C_{a}} \right) - C_{a} \log \left( \frac{t}{t_o} \right)$$

(10)

where $e_o$ is an initial void ratio under the consolidation condition at which the effective pressure is $P_o$ and the elapsed time of the secondary consolidation is $t_o$, and $C_{a}$ is the coefficient of secondary consolidation for the whole strata as follows,

$$C_{a} = \sum_{i} V_{si} C_{ai} / \sum V_{si} \cdot$$

(11)

The coefficient $C_{a}$ is a weighted average, similar to the compression index $C_e$ for each layer. Therefore, the void ratio of a stratum which consists of many layers can also be analysed similarly to the case of a single layer.

Fig. 5 shows $e - \log p - \log t$ diagram representing some paths of the variation of
void ratio. The path (1) on the figure exhibits the relation as an $e-\log p$ one obtained from the step-loading type consolidation test. On the other hand, the path (2) exhibits the relation as an $e-\log t$ one after primary consolidation at a stage for the common consolidation test. This path corresponds to a void ratio variation with time in the process of secondary consolidation under a constant effective stress.

Furthermore, the path (3) exhibits the relation for the layer at which applied effective stress is increasing proportionally with time, such as the case of underlying sediment in a stationary sedimentation basin. As the actual process seems to be as in the case of path (3) or nearly this, it is considered to be significant to examine the change of void ratio in the stationary sedimentation field by means of this simple relation.

If the sedimentation rate is constant, the effective overburden pressure on a layer which was formed before a time $t$, is expressed as

$$P(t) = mg(t(1-\rho_w/\rho_s))$$

where $g$, $\rho_w$ and $\rho_s$ are the acceleration of gravity, the density of water and the density of the solid part, respectively, and $g(\rho_w/\rho_s)$ is buoyancy applied to unit mass of the solid part. The parameter $m$ is a sedimentation rate referred to as the accumulation flux which is defined as the amount of the accumulating solid mass per unit area and per unit time. This parameter is also called the mass accumulation rate, MAR.

It is presumed that the period required for primary consolidation is significantly short in the scale of geologic time. Accordingly, the equation (10) seems to be valid in the actual strata and may be reformed to

$$e(t) = e_{oi} - C_{ci} \log (m'tg/P_o) - C_{ai} \log (t/t_o)$$

$$= \{e_{oi} + C_{ci} \log (P_o/g) + C_{ai} \log t_o\} - C_{ci} \log m'(C_{ci}+C_{ai}) \log t$$

where $m'$ is an apparent mass measured in water, that is, $m'=m(1-\rho_w/\rho_s)$. The effective overburden pressure is $P=m'tg$. As the first term of the right-hand member of the latter equation (13) does not depend on the time, the equation (13) becomes

$$e(t) = e_{oi}' - C_{ci} \log m' - (C_{ci}+C_{ai}) \log t$$

The thickness of the layer consequently decreases with the elapsed time, namely,

$$\delta(t) = \delta_o \{1+e(t)\}$$

where $\delta(t)$ is the thickness variation of a layer formed in a unit time, and $\delta_o$ is the equivalent thickness of a solid part in the layer, that is, $\delta_o=m/\rho_s$.

In these sedimentation fields, the underlying layers decrease their thickness with time through the effects of the increasing overburden pressure and secondary consolidation. Integrating the equation (15), we can obtain the thickness variation of the strata during elapsed time, thus,
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\[ D = \int_0^t \delta \{1 + e(t - \tau)\} d\tau \]

\[ = D_0 + (mt/\rho_s)\{1 + e^{0.434\{C_e \ln m' + (C_e + C_w)(\ln (t - 1))\}}\} \]

(16)

where \( D_0 \) is the initial value of the thickness of the strata; but in this case we can denote \( D_0 = 0 \) when \( t = 0 \). From above equation, the relation between void ratio and depth can be obtained by means of substituting an adequate value for the sedimentation rate \( m \) and changing the variable \( t \).

5. Application to the compiled data

Fig. 6 shows the actual relationship between age and depth in places where sedimentation seems to have continued at a constant rate up to Recent times. The ages of data plots indicated by open circles or solid lines on the figure have been determined precisely by means of microfossil analysis, fission-track technique, identification of palaeomagnetic polarity and other methods. The values of parameter \( m \) attached to the dotted line on the figure exhibit the sedimentation rate, \( \text{kg/(m}^2 \times 10^3 \text{ yrs)} \), and correspond to each relationship between the age and depth deduced from equation (16).

Some assumptions in this computation are as follows: the sedimentation rate is constant, and the values of each constant are \( e_0' = 0.4 \), \( C_e = 0.05 \), and \( \rho_s = 2.65 \text{ g/cm}^3 \). These values are nearly equal to those of the silty soils; they seem also to be a mean value for a series of strata accumulated in submerged area, such as a sedimentary basin.

A clay or a shale, however, may have more important meaning than other kinds of geo-materials. Hence the density for the more plastic material is a better indicator of the maximum pressure applied in the past. Therefore, we use other parameters, \( C_e' \) and \( C_w' \), instead of \( C_e \) and \( C_w \), in the equation (14). Namely, the void ratio of clay or shale is expressed by similar equation as (14)

\[ e(t) = e_0'' - C_e' \log m' - (C_e' + C_w') \log t \]

(17)

If the sediments are saturated by water, their density is

\[ \rho = (\rho_s + e\rho_w)/(1 + e) \]

(18)

where \( \rho_s \) and \( \rho_w \) are the density of solid and water, respectively. Then we can easily obtain the density from the void ratio based on a general assumption that \( \rho_s = 2.65 \text{ g/cm}^3 \) and \( \rho_w = 1.0 \text{ g/cm}^3 \).

As a necessary preliminary to the analysis of density distribution, let us compare the results of observation and computation for density versus depth relation. Fig. 7 shows the density versus depth relations of a clayey sediment computed from equations (16) and (17). It is clear from the figure that the density versus depth relation is strongly influenced by parameter \( m \), and that the increasing of \( m \) leads to the decreasing of the density gradient. In contrast to this, it may also be possible to estimate the sedimentation rate from the density gradient referring to this figure.
Fig. 6  The relation between the age of strata and its depth (unit of sedimentation rate $m$ is kg/(m$^2 \times 10^3$ yrs)). Niigata Basin: Boundary between the Nishi­­yama Formation and the Kaizume F., 0.85 Ma (Tsuchi, 1979); Po valley: Boundary between the Calabrian and Upper Pliocene strata, 18.2 Ma (Selli, 1967); Akita Basin: Boundary between the Tentokuji F. and Sasaoka F., 0.90 Ma (Tsuchi, 1979); Osaka Basin: Azuki tuff, 0.87 Ma (Nishimura and Sasajima, 1970); Lake of Biwa: Compiling of fission track age (Taishi, 1986); DSDP S. 474 (Leg 64): (Curby and Moore et al., 1978); DSDP S. 494 (Leg 67): (Aubouin and von Huene et al., 1980); DSDP S. 357 (Leg 39): (Pelch-Nielsen and Supko, 1974); DSDP S. 527 (Leg 74: (Moore and Rabinowitz, 1980).

Fig. 8 shows the comparison between theoretically computed and observed relations of density variation with depth. Those two results are in good agreement with each other over wide range, as seen in the figure, with the exception of two curves, no. 8 and no. 10. If the curves no. 8 and no. 10 are shifted by about 150 meter and 550 meter, respectively, in the direction of deeper depth, that is, on the right side in Fig. 8, the theoretical curves are almost identical with the observed ones.

The above theoretical curves are obtained by substituting adequate values for the constants of the equations (16) and (17). A set of optimum values for the parameters...
Fig. 7 Theoretical computation of the effect of sedimentation rate, \( m \) \( \text{kg/(m}^2 \times 10^3 \text{ yrs)} \), on the density variation with depth.

Fig. 8 Comparison of theoretical computation results and observed relation for the density variation with depth. Heavy solid line: observed relation, Light solid line: theoretical relation. Broken line: observed relation at the locality where the region seems to have been eroded significantly (refer to text).
can be obtained by comparing the results of theoretical calculation and the actual density distribution shown in Fig. 8. This is shown in Table 1. Each value of the parameter adopted shows that it is a common value in general kinds of sediments.

We now examine the density versus depth relation from the another point of view. Fig. 9 shows the relation between depth of the layer aged 1 Ma and depth of the layer having density of $2.0 \text{ g/cm}^3$. This relation approximately corresponds to the relation between a sedimentation rate and a density gradient of subsurface strata.

The observed data plot on or near the solid line derived from the theoretical computation, except the data from Site 298 of DSDP.

The above solid line is obtained by theoretical calculation and by using the same values of the parameters as those shown in Table 1. In Fig. 7, we can draw a straight line indicating the density of $2.0 \text{ g/cm}^3$ parallel to the depth axis. This line gives the depth of a layer having density of $2.0 \text{ g/cm}^3$ corresponding to each value of sedimentation rate $m$. Applying this relation to the age versus depth relation (equation (16) or

![Fig. 9](image)

**Fig. 9** Relation between depth of the layer aged 1 Ma and depth of the layer having density of $2.0 \text{ g/cm}^3$. Open circle: observed data from land area. Solid circle: observed data from wells of DSDP. Number is Site No. Solid line: theoretical relation using optimum value of $C_e/C'_e=0.6$. Broken line: theoretical relation using empirical common value of $C_e/C'_e=0.05$.

**Table 1. The values of parameters used by computation**

<table>
<thead>
<tr>
<th>$e_o$</th>
<th>$C_e$</th>
<th>$C_m$</th>
<th>$e_o'$</th>
<th>$C_e'$</th>
<th>$C_m'$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>0.1</td>
<td>0.005</td>
<td>4.7</td>
<td>1.0</td>
<td>0.6</td>
</tr>
</tbody>
</table>
Fig. 6), we can obtain the depth of layer aged 1 Ma corresponding to each value of \( m \), eventually obtaining the theoretical curve shown in Fig. 9.

In this case, the ratio of secondary consolidation coefficient to compression index \( C'_s/C'_c \) is equal to 0.6. This value is a order of magnitude larger than the common value of 0.05 reported from the general consolidation test in the laboratory. If the value of 0.05 is adopted for the analysis, the theoretical curve is represented as a broken line as shown in Fig. 9. As the time effect obtained from the laboratory is too small, we cannot explain the consolidation process found in actual strata. This discrepancy should be attributed to the difference of conditions on the consolidation process between the conventional testing method in laboratory and the \( \textit{in situ} \) conditions.

Concerning the datum at Site 298 of DSDP, on the Nankai Trough, it is clear that the point is plotted in an extreme over-consolidated region at a good distance from the standard line in Fig. 9. The sedimentation at the site is very rapid, and the thickness of sediment has been estimated to be over 900 meters during 1 Ma to present (INGLE et al., 1975).

As pointed out by MOORE and KARIG (1976) and BRAY and KARIG (1985), the fact is that as the drilling point is located exactly on the trench axis, the accretionary prism existing at the convergent plate margin has been strongly deformed, with desiccation not only by the gravimetric compaction but also by the obvious tectonic compaction.

6. Influence of erosion

Though a relative uplift associated with tectonic movement or change of sea level leads to erosion of the strata, an underlying stratum has the density corresponding to applied maximum overburden pressure, and an alteration of the relationship between density and depth takes place.

The density variation with depth at two typical regions in the Osaka Basin is shown in Fig. 10. Closed and open circles represent the data from drilling OD-1, which is situated in the depression area (Minato district, Osaka Pref.), and from drilling OD-2, which is situated in the uplift area (Miyakoijma district, Osaka Pref.), respectively. These two areas are regarded as being of similar geological constitution, from the observation of their drill cores. The upland region including OD-2, however, has been considered to be significantly eroded by uplift during the Late Pleistocene (HIZITA, 1983), and the displacement is estimated to be about 370 meter from the offset of the intercalated key bed called the Azuki Tuff. If the density distribution of OD-2 is shifted to deeper depth by 370 meters in Fig. 10, we can see a good agreement between the two density distributions with depth.

In the case of Akita Basin, if the line in Fig. 8 represented by linked small circles is shifted downward by 150 meters from the dotted line (no. 8) in the figure, it almost coincides with the theoretical line corresponding to \( m=2,000 \text{ (kg/(m}^2\cdot 10^3 \text{ yrs})} \) and the amount of the erosion is estimated to be 150 meters. The estimated value is concordant
Fig. 10 Comparison of different relations between density and depth at two localities in the Osaka Plain. OD-1: well at Minato-Ku, near shore line of the Osaka bay (region of tectonic depression). OD-2: well at Uemachi Uphill (center of tectonic upheaval zone).

Fig. 11 Estimation of the thickness of the eroded strata in Kwanto Basin deduced from the density versus depth relation together with the present model.

with the evidence of at least the two erosional periods during the Late Pleistocene, as seen from the stratigraphic examinations (IKEBE and IWASA, 1963).

The comparison of density distributions as between observation and computation in
Kwanto Basin, which is greatest scale of the Quaternary basins in Japan, is shown in Fig. 11. The observed data are from Funahashi City in Chiba Pref. (NIREI et al., 1972). Some data from Tokyo tend also to be similar to those (ENDO, 1979). The amounts of erosion and the sedimentation rate $m$ are estimated to be over 550 meters and 8,000 (kg/m²·10³ yrs), respectively. The data on geologic age of the subsurface strata related to the above results have not yet been obtained.

7. Influence of environment

As mentioned above, physico-chemical factors play an important role in the clay-water electrolyte system. Factors such as the specific area of clay, surface characteristics of grain and chemical characteristics of pore water affect the physical properties, especially the elastic moduli of argillaceous sediment (NAKAGAWA et al., 1977, NAKAGAWA and OKUDA, 1978). The void ratio of clay consisting of montmorillonite is thought to be affected by the concentration of electrolyte in pore water. Accordingly, it is expected that the density or the density distribution with depth of lacustrine clayey sediments differs from that of marine clayey sediments.

Fig. 12 shows the comparison between the bulk density of the clayey sediments under Lake Biwa and under Osaka Bay, with exception of sediments whose liquid limit is smaller than 70%:. The void ratio of marine sediments tend to decrease more than those of lacustrine sediments, and it is difficult to know whether this difference is significant or not.

Fig. 12 Comparison of density variations with depth for marine sediments and lacustrine sediments. The plots are data from core samples of which liquid limit is larger than 70%. The original data are obtained by Akai et al. (1986).
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