Visakhapatnam Chapter

Proceedings of Indian Geotechnical Conference 2020
December 17-19, 2020, Andhra University, Visakhapatnam

Effect of Strain-Rate on Stress-Strain Behavior of Dredged Material at Different Moisture Contents - An Experimental Study

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Abstract. This study presents the results of a laboratory investigation of the effects of strain-rate on the stress-strain behavior of dredged material, remolded at different moisture contents. The rate of loading or strain-rate is found to be one among the most important factors affecting the shear strength parameters of soil. In the practical world, the soils supporting various structures are subjected to varying strain-rates which may be low, intermediate and high. The objective of the current investigation is to obtain a better understanding of the strain-rate effects on strength behavior for different moisture conditions of the soil. The soil selected for this purpose was a dredged soil taken from Brain area of Srinagar city (J&K). A series of triaxial compression tests were executed on the test soil under unconsolidated undrained (UU) conditions. The rate of strain was studied from 6 mm/min to 0.24 mm/min. Consequently, three different cell pressures as 50 kPa, 100 kPa, and 150 kPa were used and soil was molded and tested at optimum moisture content (OMC) and on both sides of OMC (dry and wet). The specimen is sheared at a strain-rate and the load readings are taken for a set of deformation readings, thereby determining the deviator stresses at failure. This study supported the previous literature that the shear strength increases with an increase in strain-rate. However, shear strength was highly affected by moisture content wherein the deviator stress at failure experienced an increase with reducing moisture content irrespective of the applied strain-rate.

Keywords: Dredged material, Strain-Rate, Optimum Moisture Content (OMC), Monotonic Triaxial Compression Test.

1 Introduction

The primary requirement of the design of sustainable and resilient infrastructures is that engineering structure must withstand economically and efficiently any anticipated and unanticipated force, and whenever subjected to extreme loads, these structures should work within a reasonable time and with minimum repair capacity. Natural causes in the form of a tsunami, tornado, and earthquake and human activities like bomb blast, rocket attack, and collision are the main reasons for extreme loadings.

Blasts, missile penetration, and sudden landslides are among such loading events which may generate strain-rates of the order of 10^4/sec in the soil [1] and may also prompt catastrophic failures. Effect of strain-rate on the shear strength of soil was first studied in 1948 [2]. Triaxial compression tests were performed on sand at a strain-rate up to 115%/s and confining pressures varying from 30 to 90 kPa. The conclusions drawn from the experiments were, a 10% increase in shear strength of dry sand when tested at higher strain-rates. Consolidated-undrained (CU) triaxial compression tests conducted on compacted boulder clay shows a log-linear increase in undrained shear strength with increasing strain-rate [3] in both conditions (saturated and unsaturated). A research was conducted on the time-dependent behavior of dense Toyoura sand with strain-rates ranging from 0.00000417 to 0.0021%/s [4, 5]. It was concluded that, at low strain rates there was not a large effect of strain-rate when sheared at different but constant rates. However, a much more significant effect was noticed when changing rates during shearing. Being among the weakest of all civil engineering materials, soil often plays a critical role in the failure of the structures under catastrophic events. In the study of soil behavior under loading such as explosions, earthquakes, mine blasts, vehicle & aircraft loading, dynamic compaction, etc., consideration of the impact of strain-rate on soil behavior is important. It is widely accepted in the solid mechanic's community that the strength, constitutive behavior, and overall response of soils are highly dependent on the strain-rate.

The rate of loading or strain-rate is found one among the most important factors influencing the shear strength parameters of soil. However, another dominant factor of soil failure or deformation is moisture content. Various conditions that result in change of moisture content of soil are groundwater rising, surface water infiltration, precipitation, etc. which subsequently decreases the resilient modulus and strength of soil. A comparison was made between stress-strain properties of unsaturated specimens that were prepared at different molding water contents by different preparation techniques [6]. It was noticed that statically compacted specimens have a stiffness value larger than dynamically compacted ones, while with increasing water content, a decrease in the stiffness occurs. An increase in cohesion component with decreasing molding water content was also observed. The constrained modulus, which is the ratio of axial stress to axial strain in one-dimensional compression, is consistently higher when soil is compacted on the dry side of optimum than when compacted on wet side [7]. Triaxial compression tests on compacted specimens were performed and it was concluded that unsaturated specimens compacted at different water contents should be treated as different materials [8]. At saturated conditions, there is a slight change in secant modulus with change in confining pressure [9], whereas a significant increase in secant modulus is observed at moisture content less than 20%. From the stress-strain curve, a strain-softening behavior of loess can be seen with increase in the moisture content. When the moisture content is less than plastic limit, there is a slight increase in cohesion with increase in moisture content, while a significant decrease is observed when moisture content exceeds plastic limit. However, no such change was observed in internal friction angle.

This paper characterized the variation of deviator stress at failure during triaxial tests under different strain-rates and moisture content. The moisture content influence on deviator stress of soil under different confining pressures is also analyzed. The results are utilized to gain a better understanding of the strain-rate effects and water content on stress-strain behavior of soil.

2 Material

The soil selected for the purpose of this study was collected from the disposal site "Brain" area of Nishat Jammu and Kashmir. The soil was a dredged material from "Dal", a lake in Srinagar, the summer capital of Jammu and Kashmir. The city's lake, which is the second-largest lake in the country, is an integral part of tourism and recreation in Kashmir and is called "Jewel of the Kashmir Crown" or "Jewel of Srinagar". A huge amount of dredged material is generated from various basins of Dal Lake due to the movement of large volumes of sediment into Dal. This material can be an important reserve for many viable purposes. The material excavated may constitute gravel, soft clays or silt depending upon the kind of environment. Based on its classification, the material can be put to different uses like foundation material, construction of subgrade, reclamation, landscaping, landfill covers, and constructing wetlands for water quality improvement, bank stabilization, and creation of islands, etc. Therefore, for the utilization of dredged material in mass in different geotechnical applications, an attempt was made to examine the mechanical and physical properties. This material is difficult for certain projects due to its high moisture content and low processability. Nonetheless, treated dredged material can be used as a resource for various engineering applications and a stabilizer for improving the behavior of fine-grained soils.

Fig. 1 shows a particle size distribution (PSD) curve for the test soil. As per the Indian Standard Soil Classification System (ISSCS) the processed soil is classified as medium compressible silt (MI). Standard Proctor Compaction curve for soil is shown in Fig. 2. Corresponding to optimum conditions, the dry unit weight and compaction water content has a value of 14.8 kN/m^3 and 22.2% respectively for the standard proctor compaction effort.

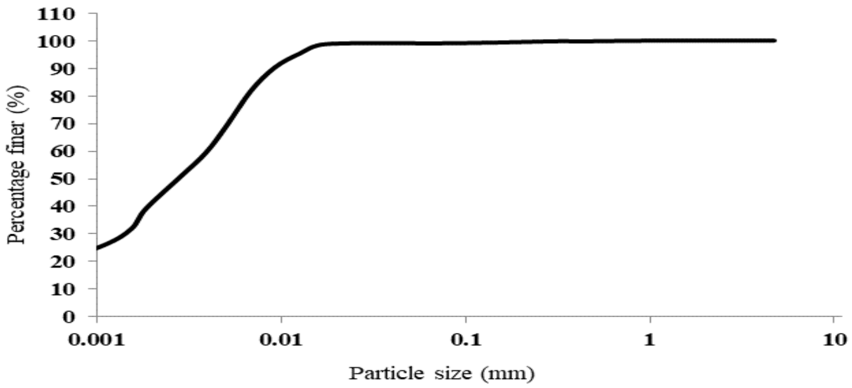


Fig. 1. Particle size distribution (PSD) curve of the test soil.

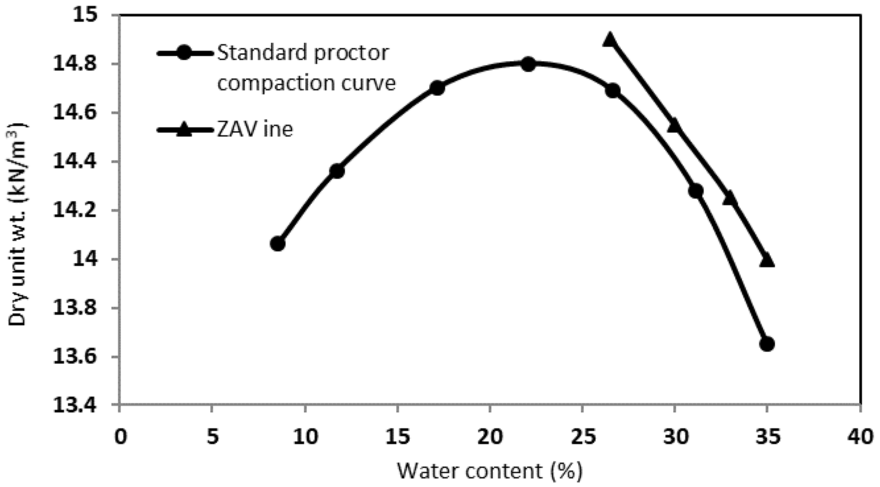


Fig. 2. Standard Proctor Compaction Curve of the test soil.

All tests were performed in accordance with the corresponding Indian standards [10 - 14]. The physical properties of the materials used are listed in Table 1.

Table 1. Basic Test Results of Soil Sample.

Parameter	Value	Unit
Field Moisture Content	54.62	%
Specific Gravity	2.4	-
D_{30}	0.0015	mm
D_{50}	0.0028	mm
D_{60}	0.004	mm
Sand fraction	1	%
Silt fraction	57	%
Clay fraction	42	%
Particle size range	<0.001 – 0.6	mm
Liquid Limit	39.5	%
Plastic Limit	26.1	%
Plasticity Index	13.4	%
PI (A-line)	14.24	%
PI (U-line)	28.35	%
Clay Mineral Type	Kaolinite	-
Classification	MI	-
Optimum Moisture Content (OMC)	22.2	%
Maximum Dry Unit Wt. (MDU)	14.80	kN/m^3

3 Experimental Approach

A series of Unconsolidated Undrained (UU) triaxial compression tests were performed on the test soil for three different strain-rates. The rate of strain was studied from 6mm/min to 0.24mm/min. Cylindrical specimens of diameter 38 mm were prepared with a height equal to twice of diameter (H/D = 2). The cylindrical mold consists of a length of steel tube with the diameter and length of the desired specimen. Fig. 3 shows the different extruded soil specimens at OMC. The three different cell pressures used for the study are 50 kPa, 100 kPa, and 150 kPa. The failed soil specimen is shown in Fig. 4.

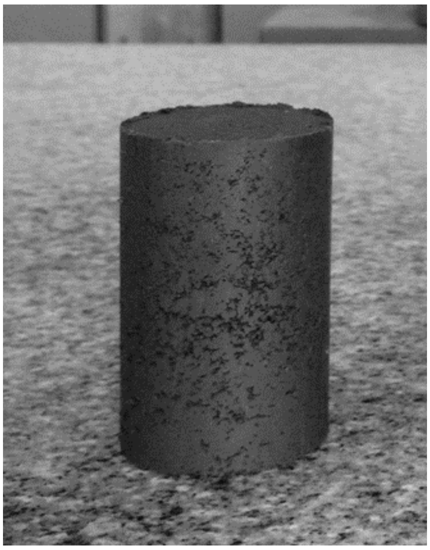


Fig. 3. Extruded Soil Specimens

Fig. 4. Sheared Soil Specimen (at OMC)

4 Experimental Results

The deviator stress (σ_d) which is the principal stress difference (σ_1-σ_3), is plotted as a function of axial strain for specimen at various OMCs. The deviator stress is given by,

$$(\sigma_1 - \sigma_3) = \sigma_d \tag{1}$$

where σ_1 is the major principal stress (axial stress), σ_3 is the minor principal stress (cell pressure) and σ_d is the deviator stress.

In this study, deviator stress at failure $(\sigma_1-\sigma_3)_f$ is used to present the undrained shear strength of the soil. During the evaluation of stress-strain curves, the deviator stress at failure $(\sigma_1-\sigma_3)_f$ is taken as either the maximum value of deviator stress from stress-strain curve in case where peak is observed or the value of deviator stress at an axial strain of 20% in case where no peak is observed.

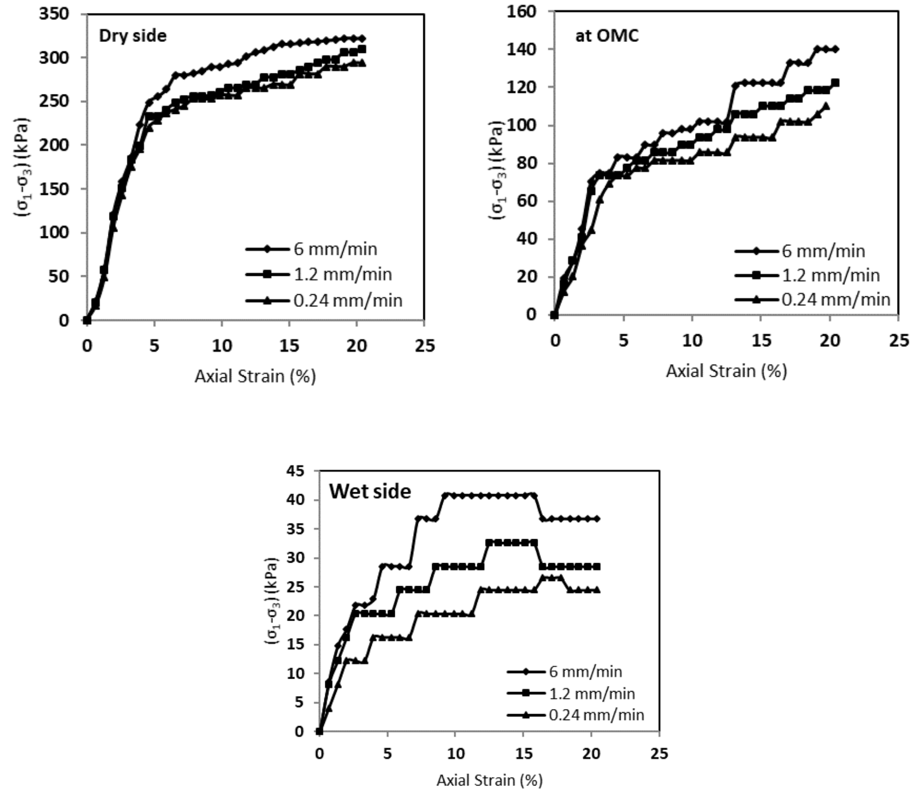
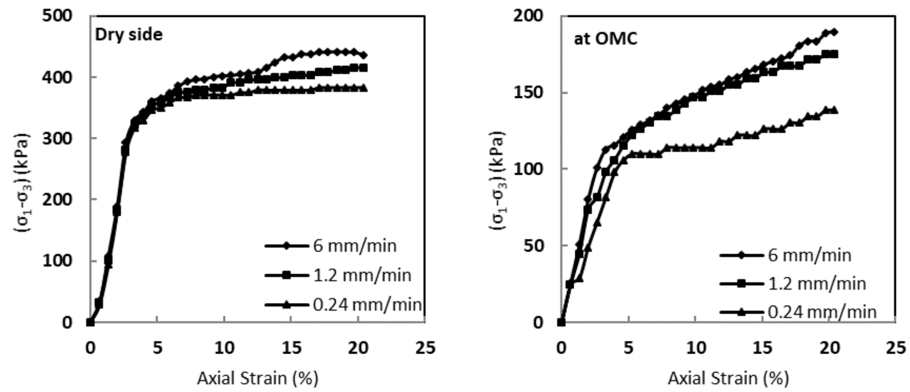


Fig. 5. Behavior of deviator stress under UU triaxial compression tests at different strain-rates and moisture content (σ_3=50 kPa).



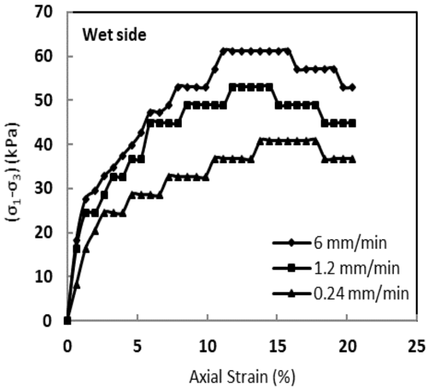


Fig. 6. Behavior of deviator stress under UU triaxial compression tests at different strain-rates and moisture content (σ_3=100 kPa).

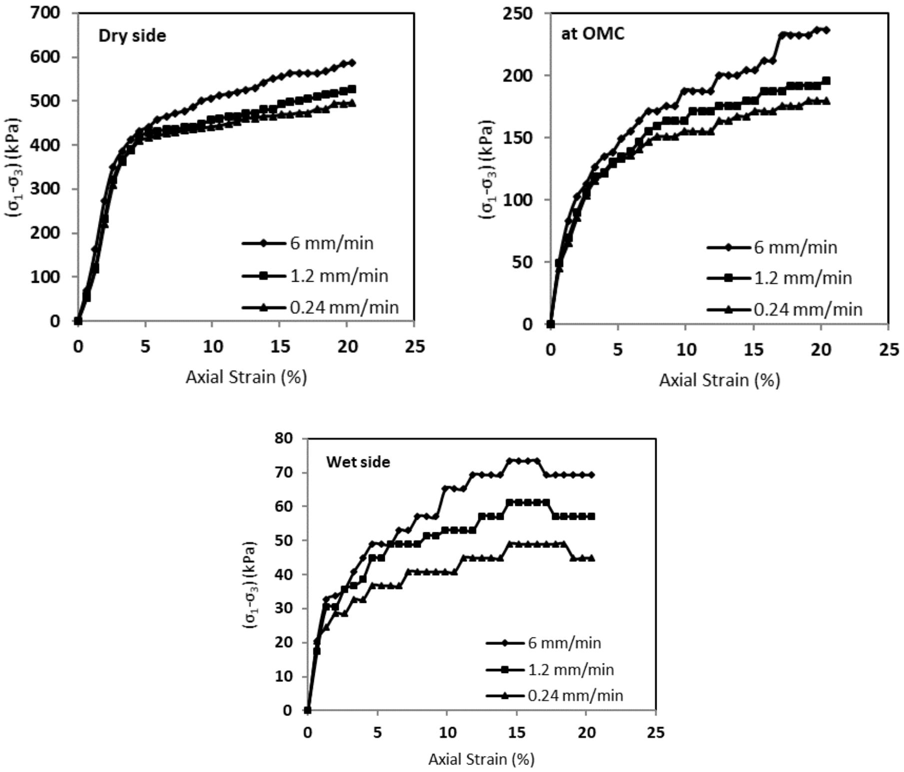


Fig. 7. Behavior of deviator stress under UU triaxial compression tests at different strain-rates and moisture content (σ_3=150 kPa).

The influence of strain-rate on the undrained deviator stress is summarized in Fig.'s 5, 6 & 7. The Fig's compare the variation of undrained deviator stress by varying axial strain from the triaxial compression tests at different moisture content. The variation of deviator stress with varying strain-rate and for same confining pressure (50 kPa) but different moisture content is shown in Fig. 5. It is observed that with increasing strain-rate, an increase in failure deviator stress occurs. The value of deviator stress at failure is maximum for highest strain-rate (6mm/min) and minimum for lowest one (0.24mm/min). Also, it is observed that at failure the value of deviator stress is more at the dry side of optimum, less at OMC and even lesser at the wet side of optimum. No peak is observed when the specimen is sheared at dry of optimum and at optimum, but the significant peak is observed when sheared at the wet side of optimum.

Similarly, deviator stress variation at a cell pressure of 100 kPa for different moisture content with varying strain-rates is shown in Fig. 6. Similar results were observed as observed for cell pressure of 50 kPa. The deviator stress is found to be more for highest strain-rate (6mm/min) and minimum for lowest one (0.24mm/min). Also, it is observed that at failure the value of deviator stress is more at the dry side of optimum, less at OMC and even lesser at the wet side of optimum. No peak is observed when the specimen is sheared at dry of optimum and at optimum, but the significant peak is observed when sheared at the wet side of optimum.

Similarly, the variation of deviator stress at a cell pressure of 150 kPa for different moisture content with varying strain-rates is shown in Fig. 7. Similar results were observed as observed for cell pressure of 50 & 100 kPa. The deviator stress is found to be more for highest strain-rate and with decreasing strain-rate a decrease in deviator stress is observed. Also, it is observed that at failure the value of deviator stress is more at the dry side of optimum, less at OMC and even lesser at the wet side of optimum. No peak is observed when the specimen is sheared at dry of optimum and at optimum, but the significant peak is observed when sheared at the wet side of optimum.

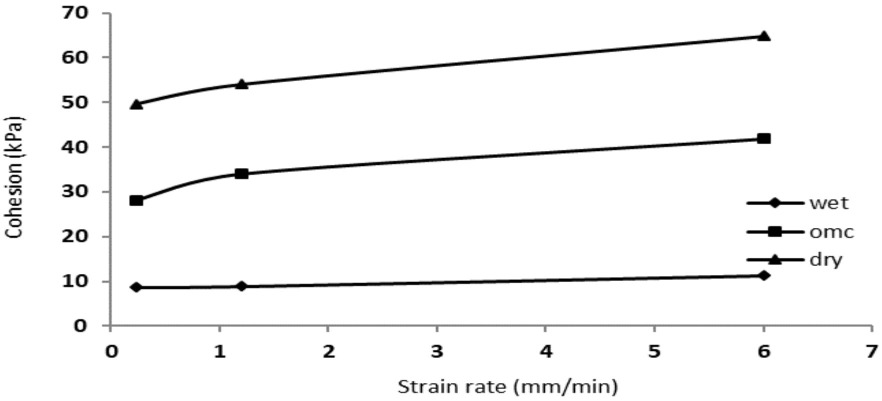


Fig. 8. Variation of cohesion (c) with strain-rate at different moisture contents.

The effect of strain-rate on the cohesion of soil is presented in the form of a graph (Fig. 8). It can be seen from the Fig. that cohesion increases as the strain-rate increases. The cohesion mobilizes more at high strain-rate (6mm/min) and less at low strain-rate (0.24mm/min). Again, it is observed that at dry side of optimum cohesion obtained is higher and with increase in moisture content cohesion decreases.

5 Conclusions

The conclusions that were drawn from the series of experiments are as follows:

1. The strain-rate variation leads to the shear strength variation of the soil. With increasing strain-rate, an increase in $(\sigma_1-\sigma_3)_f$ was observed in the stress-strain curves. The maximum value for $(\sigma_1-\sigma_3)_f$ was observed for the highest strain-rate (6mm/min) and minimum value for the lowest strain-rate (0.24mm/min).
2. Throughout the tests, the deviator stress mobilizes largely at dry side of optimum and with increase in moisture content it decreases.
3. By examining stress curves, it is seen that the $(\sigma_1-\sigma_3)_f$ increases with increasing confinement pressure. The maximum value of $(\sigma_1-\sigma_3)_f$ was observed for 150 kPa and minimum for 50 kPa.
4. An increase in cohesion (c) of soil with decreasing moisture content was also observed.
5. Clear shear bands were observed at the dry side of OMC while no bands were observed at OMC and dry side of OMC.
6. Based on these tests, it must be concluded that to obtain significant increases in strength takes a rate of strain equivalent to a fast-transient test.

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