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Effect of consolidation on local scour around bridge pier in cohesive soil

1. Dr. Abdul Karim Barbhuiya
Associate Professor
Civil Engineering Department
NIT Silchar, Assam, India

2. Tamasa Chakma
Assistant Professor
Civil Engineering Department
NIT Agartala, Tripura, India

ABSTRACT

The scouring process is very complicated involving 3D modification of flow around piers. In this present study, experiments were conducted in a flume, to study the scour around bridge pier in cohesive soil. The test samples investigated in this study are mixtures of clay and silt with variable compositions and different consolidation times. Effects of consolidation in terms of dry density on equilibrium scour depths and on time variation of scour were studied. Further, the variation of scour depth on percentage of clay and silt is also investigated. Moreover, the geometry of the scour hole at different clay and silt content and also with time variation was studied. It is observed that the depth of scour holes decreases with the increase of dry density due to consolidation. Again, it is found that the depth of scour hole also decreases with the increase of clay and silt content.

KEY WORDS

consolidation, local scour, cohesive soil, dry density, scour depth.

1. INTRODUCTION

In engineering design and safety, the effects of alluvial river flow around a bridge pier is an important practical problem which results into scour. The main cause of concern in stability of bridges founded in river beds in lowering of river bed level caused by river flow around bridge elements such as piers, abutments and spur dikes and is termed as 'local scour'. The erosion behaviour of cohesive sediments around an obstruction plays a dominant role in engineering problems. Compared with non cohesive sediment, cohesive particles have a large specific surface area which is defined as the surface of the particles per unit weight. The fine sediment particles are connected with each other as a result of strong influences of the electrochemical reaction on the surface of the particles in water. The finer the sediment particles, the more important the electrochemical effects are. Such effects are favourable for the sediment particles to become more stable against erosion. In the course of consolidation of fine sediment particles, the texture of deposits change progressively into a denser state under the action of its own weight or other external forces, and the deposits acquire a stronger cohesion. The resistance against erosion increases with consolidation time, with bulk density as an indicator to represent the erosion resistance of the consolidated sediment. Detailed studies on the mechanism of scour around bridge piers and abutments were made amongst others by Laursen and Toch, (1956), Nakagawa and Suzuki (1975),Raudkivi and Robert Ettema, (1983), Melville and Sutherland (1988), Ettema (1990), Kandasamy and Melville (1998), Sheppard and Miller (2006), Dunn (1959), Bohan (1970), Steven and Ruff (1982), Shuyou and Fang (1991), Sekine and Iizuka (2000) Jennifer (2005), Dey and Barbhuiya (2004, 2005), Montanari (2006), Sheppard and William Miller Jr (2006), Tan Guang-ming, Wang Jun, Shu Cai-wen, Lai Yong-hui(2006). Underestimation of the depth of scour and its areal extent results in design of too shallow a foundation which may consequently get exposed to the flow endangering the safety of the bridge. Overestimation of the scour depth results in uneconomical design. Therefore, knowledge of the anticipated maximum scour depth for design discharge is essential for a proper design of the foundation of the bridge piers, abutment etc. The aim of the present study is the effect of consolidation time and sediment composition of clay and silt on scour rate of the cohesive sediment around bridge piers.

2.EXPERIMENTAL SETUP AND PROCEDURE

1. Experimental setup: Experiments were conducted in a 16 m long, 0.9 m wide and 0.7 m deep horizontal flume. The test section was located 10.90 m from the upstream end of the flume. At the inlet section, there was a vertical steel screen covering the full cross-section for damping the flow disturbances through which water entered into the flume as shown in **Fig.1.** An adjustable tailgate was installed at the downstream end of the flume to control the flow depth. The choice of the flume and the location of the test section were made in such a way that— (a) the width of the flume was wide enough to have three-dimensional flow and (b) the flow became fully developed before it reaches the test section. The flume was connected to the water supply system in the laboratory. A sediment trap was constructed in the downstream side, having a length of 1.5 m to arrest the scoured sediments. A centrifugal high discharge pump was used to pump water into the flume with a discharge of 26.9 lit/sec .The discharge pipe of diameter 20.32 cm and control valve to regulate the amount of discharge into the flume. The pump is driven by a 15 horse power motor under 1440 rpm. It is a three-phase continuous type motor. The average velocity is found to be 13.4 cm/sec.

2. Sample Preparation: The test samples used in this experimental work are divided into 6 groups according to their compositions. The size distributions are shown in **Fig.2**. The median size d_{50} determined from the particle size distribution curve for different sediments were found to be 0.18mm, 0.145mm, 0.12mm,0.078mm,0.075mm and 0.048mm respectively and clay content ratio of 0%, 20%, 40%, 60%, 80% and 100% respectively.

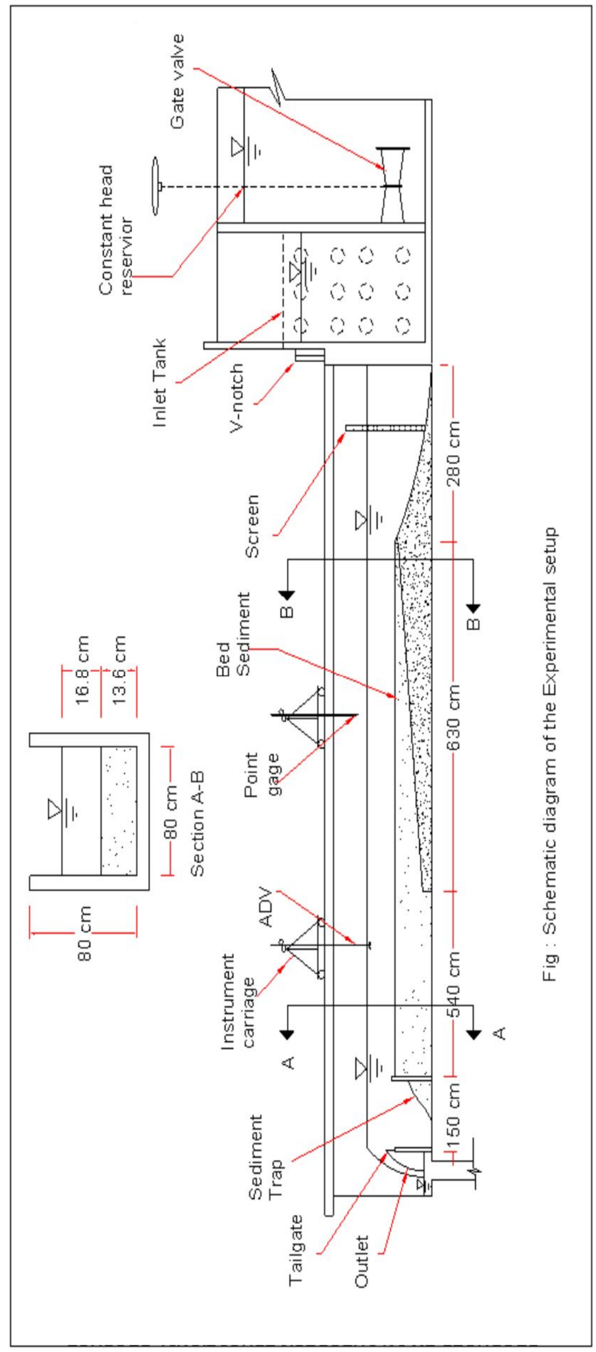

Fig.1: Sketch of experimental setup

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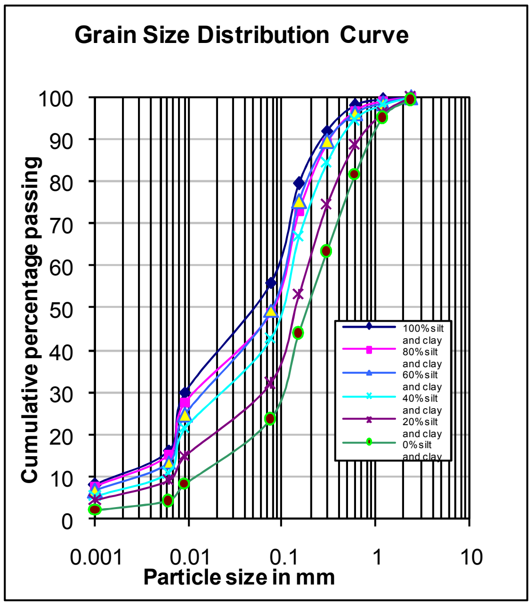

Fig. 2: Grain size distributions of samples

3. Experimental Procedure: Each group of the sample is mixed with water and left for consolidation. The consolidation period for each sample are 1d, 5d, 10d, 15d, 20d, 30d, 50d and 60d. After that dry density of different samples were found out. Nine experiments were carried out which has been divided into two parts. In the first set four tests were carried out with same 100% clay and silt content with an obstruction size of 75mm diameter with different dry densities as shown in **Table 1.** In the second set five tests were carried out with 0%, 20%, 40%, 60% and 80% clay and silt content with same obstruction size of 75mm diameter.

Table 1: First set of test (with consolidation)

Expt. No.	Silt and clay (%)	Sand (%)	Obstruction size, D(mm)	Dry density, ϒ(g/cc)
1	100	0	75	1.2
2	100	0	75	1.22
3	100	0	75	1.578
4	100	0	75	1.682

In the first set of experiment, the 100% clay and silt sample was used and was placed in the flume at the area provided for placing of material. The clay and silt sample was thoroughly mixed with water and compacted gently. Before leaving the bed to settle down completely, the obstruction was placed exactly at the centre of the bed and a smooth finishing was provided. Then the bed was left as it is to drain out water and to settle down completely. Four of such similar experiments were carried out to check the consolidation variation having different dry densities. In the second set of experiments an obstruction size was kept as constant but the percentage of clay and silt content was changed. In the second set the dry density was not taken into consideration. The depth of water and velocity of flow of water was kept as constant. While performing the experiments initial bed reading was taken before the start of the experiment. During the process of the experiment a scour depth reading was taken as the function of time. Then with the help of a periscope the scour depth reading was taken at every interval of time such as 30min or 1 hr. Finally, the bed condition was observed and noted down throughout the flume. The geometry of the scour hole was taken with the help of a ruler or a scale. The final scour hole length was noted down. The readings were recorded and analysis was carried out.

3. RESULTS AND ANALYSIS

The following analysis are based on the experimental results.

1. Dry density during the course of consolidation: It has been observed that during the course of consolidation, deposits change progressively into a denser state, and eventually they have a relatively high dry density with a strong cohesion. It is necessary to consider the variation of the dry density at different stages of consolidation and the dry density can be used to reflect the effect of consolidation on scour process. It is seen that in the early stage of consolidation, the dry density increases very fast. After several days the dry density reaches nearly steady values. A graph showing dry density versus consolidation of different clay and silt content is shown in **Fig.3.**

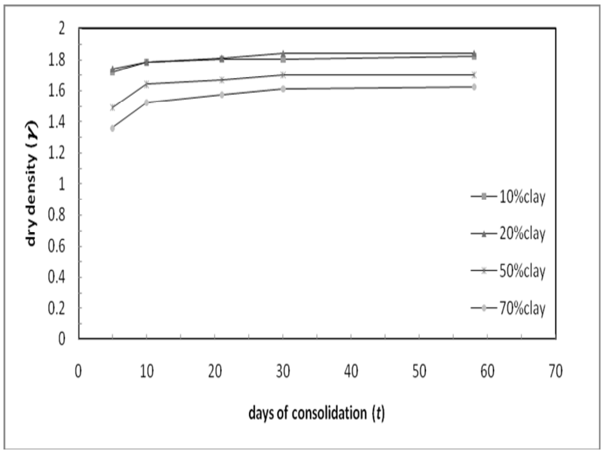

Fig.3: Dry density versus consolidation time.

2. Scouring process and monitoring of deepest scour: From the experimental observations it is found that initiation of scour occurred in either from wake or at the sides of the obstruction. The different bed materials were consolidated for different time period. In 100% clay sample, scouring occurs at a fast rate which was consolidated for one day as compared with the ones which were consolidated for more days. The scouring which occurred at the sides later turned into the entire area where the pier was fixed. Maximum scouring occurred at the upstream portion and the shape of the scour hole was approximately circular. With lower clay content scouring started very quickly, whereas it took much longer time with highly cohesive material. The maximum scour depth was found at upstream of the obstruction in all experiments. However, in soil with silt and clay content at or above 30%, the scour depth on both sides and in the wake of the obstruction is found to be about the same as the maximum scour depth. The scoured sand in the soil mixtures deposited downstream and formed a bar, while the clay particles were in suspension during the scouring process and were carried out by the flowing water.

The initiation of scour is mainly due to the accelerated flow and the formation of flow induced vortices in the vicinity of an obstruction causing erosion of sediments particles. The approach flow velocity goes to zero at the upstream face of the pier. Since the flow velocity decreases from a maximum at the free surface to zero at the bed, the stagnation pressure decreases with distance from the water surface and this pressure difference drives the flow downstream. A recalculating eddy (primary vortex) is formed when the flow impinges with the seabed; the resulting vortex system wraps around the cylinder and trails off downstream. The main scouring force is the primary vortex system, which develops in front of the cylinder. Flow pattern in the wake system are formed by the rolling up of the unstable shear layers generated at the surface of the obstruction and these are detached from both the sides of the obstruction at the separation line.

Analysis of data on scour around an obstruction in cohesive sediments has revealed interesting aspect about the process of scour. In cohesive sediments, the geometry, location and extent of scour hole are found to be significantly different from those in cohesion less sediments. Observation revealed that scouring in sediments having silt and clay content between 5% to 30% commenced from the sides of the obstruction then propagates to the upstream along the sides of the obstruction and met the nose of the obstruction. The time for scour to happen is very fast and also reached equilibrium very fast. The scour depth then increased rapidly creating the deepest scour hole at the nose of the obstruction. For sediments with silt and clay content ranging from 60% to 90% a similar behavior was observed but the deepest scour is found to occur at the sides and nose of the obstruction. For sediments with higher silt and clay content, i.e. more than 50% scour initially developed at the obstruction sides, and then propagate towards the nose of the obstruction. The scour depth decreases with the increased in clay content and the time variation also increased respectively. It was observed from the experiment that at smaller obstruction size the scour depth also is less and at the larger obstruction size the scour depth is more, the shape of the scour hole is cone shape. The horseshoe vortex is more prominent when the obstruction size is large. Whether the obstruction size is small or large the maximum scour depth was found to be at the front (nose) of the obstruction. The depth of the water flow is kept at 80mm so that it does not influence scouring of the bed. In another case of the experiment when the clay content is changed it was observed that the sand particles is coated with clay all around their surface, so when the silt and clay content is between 5% to 30% in the mixture the particles tends to dislodged and detached from each other and get deposited at the downstream. The time required for scouring is minimum but scour hole is maximum and reached equilibrium stage very early. But when the silt and clay content is between 60% to 90% the particle from a bulk of mass together which is very difficult to detach them due to the physico chemical properties of cohesive soils. The time required for scouring is maximum as the obstruction sizes increases and the clay content decreases.

At the beginning of the test for time variation versus silt and clay content present in the mixture is also measured. We need to be more careful and more precaution should be taken so that unnecessary and undesirable scour hole may develop at the start of the experiments. The motor is allowed to turn on and off for several interval of time and very slowly. A full discharge is allowed when the bed has attained stability, then the reading is started taken with very small time interval.

3. Variation of scour depth with dry density: The scour process in cohesive, fine grained soil is different from that in non cohesive, coarse grained soils. During the course of consolidation, deposits change progressively into a denser state, and eventually they have a relatively high dry density with a strong cohesion. Thus, it is necessary to consider the variation of the dry density at different stages of consolidation, and the dry density can be used to reflect the effect of consolidation on scour process. It can be seen that in the early stage of consolidation, the dry density increases very fast. After several days, the dry density reaches nearly steady values. The closer the dry density is to its steady value, the more difficult the deposits are scoured. **Fig.4** shows a variation of dry density with scour depth.

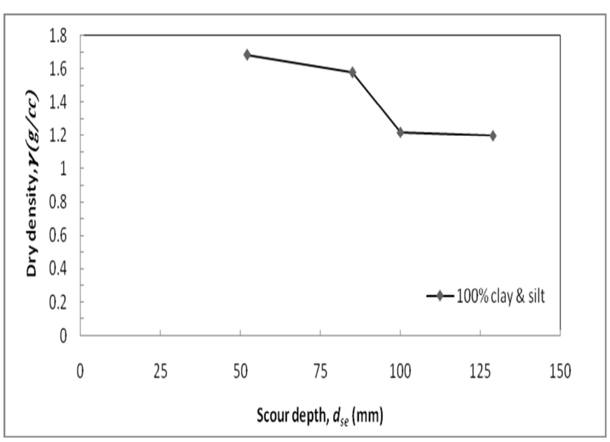

Fig.4: Variation of dry density with scour depth.

4. Variation of scour depth with clay and silt content: In cohesive sediments, the geometry, location and extent of scour hole are found to be significantly different from those in cohesionless sediments. Observations have shown that scouring in sediments having silt and clay content between 0% to 40% started from the sides of the pier and then propagates to the upstream along the sides of the pier and met the nose of the pier. In this case, scouring occurs very fast and reached equilibrium condition. The scour depth increases rapidly by creating the deepest scour hole at the nose of the pier. For sediments with clay and silt content ranging from 60% to 80% a similar behavior was seen but the maximum scouring was seen at the sides and the nose of the pier. Here the scour depth decreases with the increase in clay and silt content and takes longer time to reach the equilibrium. The shape of the scour hole is conical with clay content of 60% to 80% and the shape is circular with clay content of 5 to 40%. When the clay content is changed it is seen that the sand particles is coated with clay all around their surfaces, but when the clay content is in between 0% to 40% the particles tends to get dislodged and detached from each other and gets deposited at the downstream. Here, time required for scouring is minimum but the scour hole is maximum and reached equilibrium stage very early. In case of higher clay contents particles are very difficult to detach. Variation of scour depth with clay and silt content is shown in **Fig.5** and variation of dry density with different clay and silt content is shown in **Fig.6.**

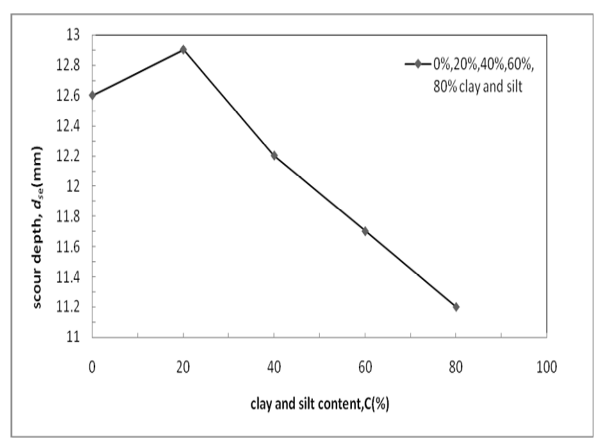

Fig.5: Variation of scour depth with clay and silt content.

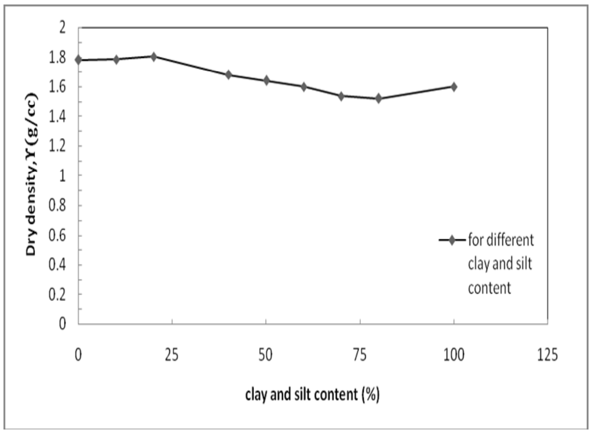

Fig 6: Variation of dry density with various clay and silt content.

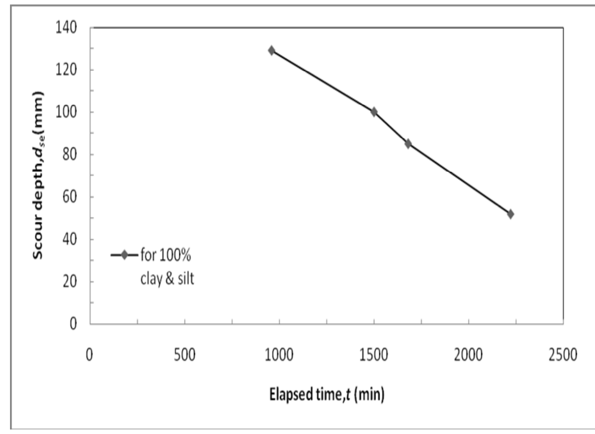

Fig 7: Variation of scour depth with elapsed time for 100% clay and silt content.

5. Time variation of scour depth around pier: Time variation of scour depth around piers is an important vision. In cohesive soils scour phenomenon is very much different from that in non-cohesive soils. Scouring process is much slower in cohesive soils and mainly dependent on the soil properties so the equations available for non cohesive sediments for time variation cannot be applied to cohesive sediments. Therefore, the cohesive materials needs to consider the time variation and soil properties. Time variation of scour depths are shown in **Fig.7 to 12.** From the figures it is seen that, the rate of scour for sediment mixture with less silt and clay content is more in the initial period and decreases with time and reaches the dynamic equilibrium condition within 20 hours. But with more clay and silt content the rate of scour is very less in the beginning and increases with time and again decreases and reach to equilibrium. The time to reach the equilibrium is very large particularly for sediment with clay and silt content of about 80%. For bed sediments with 60% to 80% clay and silt content it is found that the scour hole sometimes decreases with time which is due to the deposition of material from the slopes due to shear failure.

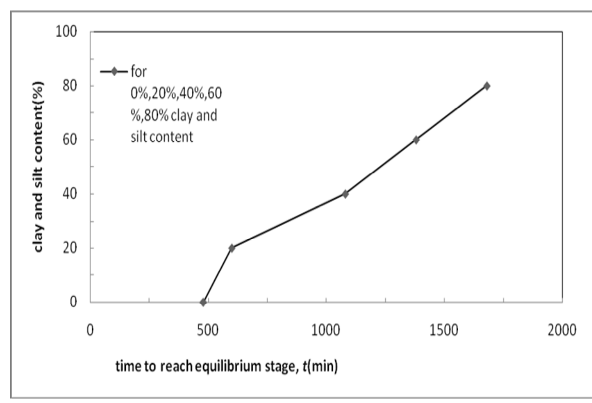

Fig 8: Variation of clay and silt content with time to reach equilibrium stage for 0%, 20%, 40%, 60%, 80% clay and silt content.

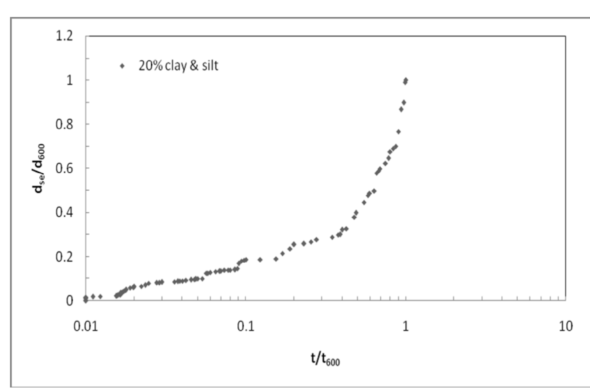

Fig 9: for (20% clay and silt)

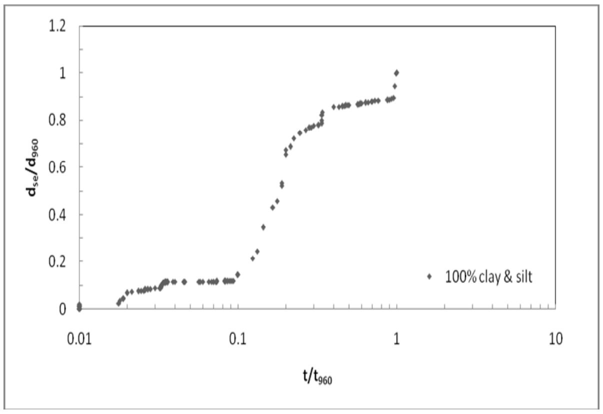

Fig10: for 100% clay and silt (without consolidation)

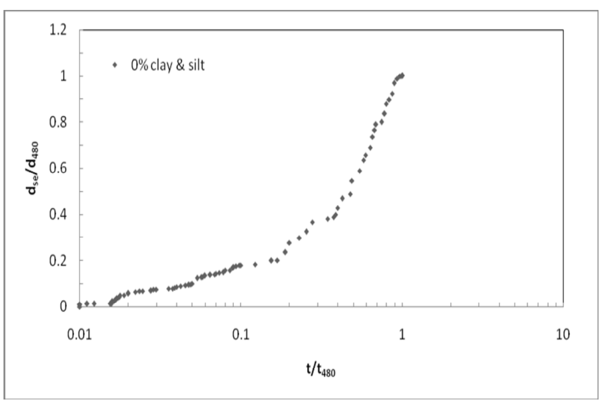

Fig 11: for (0% clay and silt)

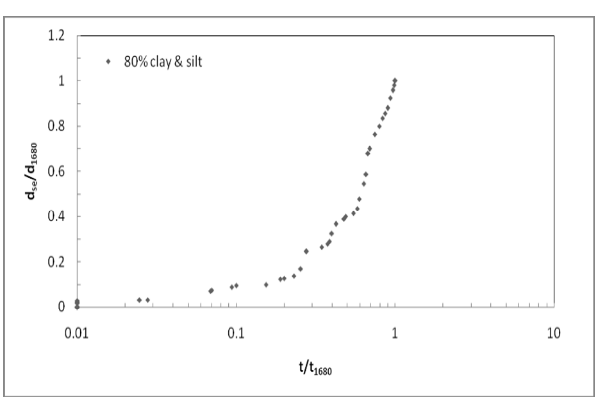

Fig 12: for (80% clay and silt)

6. Geometry of the scour hole: From the experimental results it is seen that the scour volume increases with increase of sediment size and pier size. The scour hole around the pier is produced due to the increase of velocity of the flow around the pier and formation of vortex. The system of vortices producing local scour are the horseshoe and wake vortices, which combine to produce a scour hole with its maximum depth around the pier. From the experiments of 100% clay and silt content having different dry densities (the contour diagram are shown in **Fig. 13 & 14**) it is seen that the scour hole length decreases with the increase in dry density and from the experiments of different clay and silt content without consolidation it is seen that with the increase of clay and silt content steepness of the slope increases and vice versa**.** With the increase of clay and silt content the scour at the base decreases.

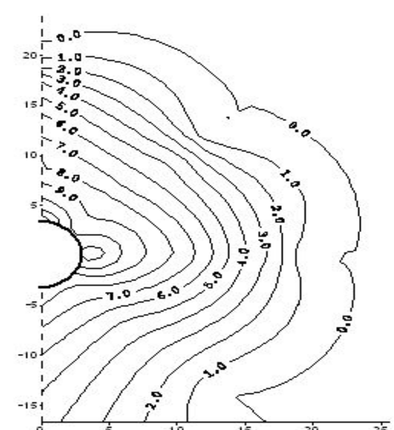

Fig 13: Contour diagram of scour hole with 100% silt and clay having dry density 1.2 g/cc.

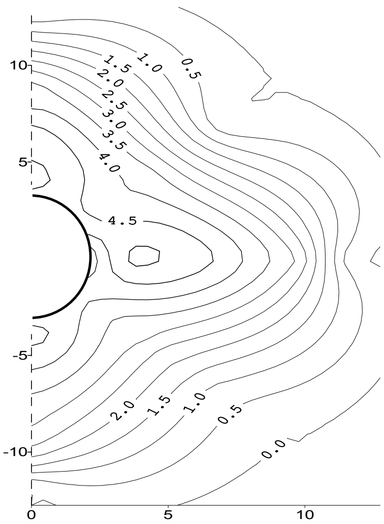

Fig 14: Contour diagram of scour hole with 0% silt and clay

4. SUMMARY

Experiments were conducted to study the effect of local scour around bridge pier in cohesive soil. The equilibrium scour depth decreases with increase in dry density of a constant clay and silt content and increases with increase in sediment size. The time variation of scour depth shows a series of parallel lines. The scouring process, shape of scour hole and maximum scour depth depends on nature of clay and silt content. The side slope of the scour hole becomes steeper with the increase of clay and silt content and maximum scour depth decreases.

5. CONCLUSIONS

1. Due to the gravitational action or other external forces, the cohesive sediment becomes denser and more difficult to be scoured.
2. Dry density is a function of consolidation time. It is found that equilibrium scour depth decreases with the increase of dry density.
3. Rate of scour also decreases with the increases of dry density.
4. For different percentage of clay and silt content, the experimental results have shown that with the increase of clay and silt content the scour depth decreases.
5. The wake vortex was found to have significant effect in initiating scour in cohesive materials.
6. Maximum scour depth was observed to occur at the upstream of the obstruction in all experiments.

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