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Using Nanostructures to Control Local Scour of Bridge Piers for Steady and Unsteady Flows

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ABSTRACT

Local scour is one of the well-known reasons causing instability of bridges, leading to fracture. Reasons reducing the scour depth in the vicinity of bridge piers are of utmost importance. There are many solutions proposed to decrease the scour depth of bridge piers. In this paper, a non-structural and eco-friendly solution is proposed to reduce scour by using nanostructured materials due to their water resistance. These materials are sediments around the base of the bridge mixed with a material referred to as nano-clay. Experiments were undertaken to investigate the scour of a bridge pier 35mm in diameter in a 10m long and 0.4m wide channel, which has a slope of 0.001. With the concentration of 1% of nano-clay in the floor sediments, the experimental results indicated a decrease in scour depth by 44.23% for steady flow and by 63% for unsteady flow. The minimum decrease in scour depth obtained is 41.6% and 56% for steady flow and unsteady flow, respectively.

KEYWORDS: Bridge pier, Local scour, Nanostructured material, Steady flow, Unsteady flow.

INTRODUCTION

Rivers are among the most important elements of watersheds, where precipitation–runoffs, land erosions and human activities are common processes and interact with each other. Many problems occur between river systems and hydraulic structures, which are mainly caused by basin sediment transport to rivers through runoffs. Within floods, flow rate and flow velocity are increased significantly, transferring sediments from the riverbed and the surroundings of bridge piers, thus leading to the creation of washed-up areas on piers (Richardson and Davis, 2001). Studies indicated that scour is one of the most important factors causing collapse of bridges (Melville and Hadfield, 1999). Therefore, how to decrease and control the depth of scour drew much interest to many researchers. Some methods have been proposed either to deal with erosion itself or its cause; as for the prior, bed particle transport can be prevented using different materials, such as riprap or protective gravels around the bridge piers and as for the latter, measures are taken to remove eruptive factors, such as secondary flows and horseshoe vortices (Melville and Sutherland, 1988).

Intensity and location of scour could be greatly affected by many geometric and hydraulic parameters. Froehlich (1989) explored the effect of pier shape on scour maximum depth and concluded the pier shape to be one of the most important and effective parameters in his study. Breusers and Raudkivi (1991) investigated the effect of flow angle of attack on bridge piers and

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concluded that with increasing angle of attack, the location of scour maximum depth moves from front to back along the pier sides. Chiew and Melville (1987) and Alabi (2006) investigated the effect of narrowing magnitude of channel width on scour depth and concluded that contraction and narrowing of the channel path can result in an increase in erosion and transportation of sediments and a decrease of water level in the channel.

Kandasamy et al. (1989) and Ettema et al. (2006) investigated the effect of flow depth on scour and vortex production around scour location and concluded that scour depth is affected by the flow depth at small ratios of flow depth to pier diameter; while at medium ratios, the scour depth is affected by both flow depth and pier length.

In recent decades, many researchers have undertaken studies on scour in steady flows from different aspects, such as equilibrium depth, time variations, scour in clear water and sediment transport conditions, as well as scour in uniform and non-uniform sediment conditions. However, when flood occurs, flow in rivers becomes unsteady and in these conditions, maximum scour depth will occur and thus bridge piers have the highest possibility of collapse (Banihashem, 2005). Researchers also indicated that in unsteady flow condition, maximum scour depth is smaller than that in steady flow condition, implying that it may be reliable to design bridges by considering them in steady flow condition. Although scour could occur at any time, its occurrence is far more likely to happen in flood conditions.

However, only a few studies have been undertaken on the effect of unsteady flow condition on scour depth. Chang et al. (2004) investigated the effect of steady and unsteady flow conditions on final scour depth, using stepped hydrographs based on a 7-hour base time and different flow rates and peak times. Their results indicated that flow rate at peak time has a significant effect on scour variations; however, no significant difference of local scour depth is observed when a change in the time to reach the peak is appropriate. Tregnaghi et al. (2010) investigated the effect of hydrographic time delay on local scour in clear water condition. In their study, triangular hydrographs with time delay of up to three times the peak time were examined. Their results indicated that the actual decrease in scour depth, compared to the theoretical depth, is related to the flood flow characteristics. Furthermore, Lai et al. (2009) examined the effect of hydrograph time variations on pier local scour in clear water condition, analyzed scour depth values on the rising stage of the hydrograph and proposed a relationship to estimate the scour maximum depth in uniform sediment condition. Borghei et al. (2012) conducted experiments to assess the scour process and the influence of various parameters on the maximum scour depth in unsteady flow condition. They found that for varying peak time, a subtle variation in maximum scour depth occurs. Also, this research confirmed that the effect of several triangular hydrographs with similar peak flow rates is roughly equivalent to the effect of one triangular hydrograph with the same corresponding peak flow rate and base time. Hager and Unger (2010) investigated the effect of flood with a peak flow rate on bridge pier scour in clear water condition, with non-cohesive and uniform-sized sediments. Through both theoretical and experimental analysis, it was found that scour more likely occurs for hydrographs with longer time delay and a relationship was proposed for the calculation of scour depth from particle Froude number based on the maximum velocity and average particle size. Ebrahimi and Samani (2011) further investigated the effect of triangular hydrograph shapes on maximum scour depth. Results indicated that hydrographs do not have a shear role in influencing scour and that with an increase in the base time of hydrograph and peak flow rate, maximum scour depth increases. Using various triangular hydrographs with a 9.5 l/s base flow and 91 l/s flow peak, Guney et al. (2011) reviewed the amount of scour and bed profile in the vicinity of cylindrical piers in unsteady flow condition. Mortazavi (2012) concluded that from downstream flow control, two significantly different results can be obtained for the occurrence procedure of maximum scour depth with an increase in flow rate, which means that in terms of controlling the flow downstream, increasing the maximum scour depth is associated with an increased flow peak. Velocity variation on hydrograph steps is the major difference between the variation procedures of scour final maximum depth in these two conditions. Although scour procedure varies with hydrographs of different base and peak times, his results indicated that peak flow rate is far more influential on maximum scour depth, rather than the two parameters mentioned; base and peak time.

To control scour at bridge piers, several methods have been proposed. Using riprap covers and pile protectors to control and reduce the depth of scour was investigated by Worman (1989) and Lauchlan and Melville (2001), respectively. Furthermore, Chio (1992) proposed a means by creating notches on the perimeter of piers to prevent and control scour. His experiments indicated that changing the dimensions and location of notches can effectively decrease the depth of scour up to 20%. Kumar et al. (1999) also investigated the effect of notches on scour depth. In general, these methods can cause problems, such as structure instability, river sediments, hydraulic disturbance and more importantly, disruption on the ecology of the river. For this reason, an optimal solution is based on the minimization of the mentioned problems to decrease the depth of scour. To achieve the optimal solution, in this paper, as an innovation, nanostructured materials (nano-clay) are used to reduce the maximum depth of scour, which could be undertaken by mixing the nanostructured materials with materials in the vicinity of piers, thus resulting in a reduction of scour depth due to increased material strength. Nano-material sizes vary from 1 to 100 nm and have been widely used in various engineering designs. Research studies that have been undertaken in the field of nanostructured materials and concrete mixture proved an increase in concrete strength and impermeability by utilizing nano-materials (Chong and Garboczi, 2002). Additionally, in several papers, the effect of using nano-materials to improve the concrete channel strength has been confirmed (Khosravani-Moghaddam and Ghorbani, 2012). With utilizing cement, concrete and nanostructured materials, researchers have acquired a nano-composite structure that can save costs in addition to the strengthening of cement and concrete. Given the limited studies on the topic, experiments were undertaken on the utilization of nanostructured materials to improve riverbed materials, especially at hydraulic structures, such as bridge piers.

In our experiments, new nanostructured materials were used to reduce the maximum depth of scour in the vicinity of bridge piers. Considering the importance of hydraulic structures' collapse, particularly caused by flood, experimental conditions were set to be unsteady in order to have a more realistic and economical prediction of scour maximum depth around the bridge piers. To the authors' knowledge, there is no study on using nanostructured materials around bridge piers. Experiments showed that the utilization of nanostructured materials with 1% concentration reduces maximum scour depth and that the amount of this reduction increases as the flow rate increases. The maximum scour depth has decreased from 48 mm to 17 mm; i.e., a 63% decrease in unsteady flow and a 23.44% decrease in steady flow conditions. Even at a minimum flow rate (8 l/s), the effect of utilization of nano-clay material in reducing maximum scour depth was found to be 56% at unsteady flow and 41.6% at steady flow, respectively.

Equipment and Materials Used in Experiments

Experiments were undertaken in a plexiglas flume at the hydraulic laboratory, Gorgan University of Agricultural Sciences and Natural Resources as shown in Figure 1. The flume is 9.5m long with a rectangular channel cross-section of the height and width of 40cm. A sluice gate was prepared to control water depth in the channel. In order to reduce clear water turbulences, a reservoir and a grid plate were located at the flume inlet. As can be observed in Figure 1, bottom of the channel was raised to a height of 15 cm at a distance of 3 metres from the entrance, using a metal platform. In the middle of the 3m long channel, the bottom was covered by sand which was prepared for scour experiments, where piers were located and installed. According to scour experiment criteria, the diameter of cylindrical pier was considered to be 35 mm. In all experiments, channel longitudinal slope was set as 0.001.

Flow rate (and consequently the Froude number) is an important flow parameter, which was controlled by a device to obtain flow rate *via* pump frequency variations, as seen in Figure 2.

The experimental channel is illustrated in Figure 3A. A digital level gauge with the precision of 0.01mm was used to calculate the depth of scour holes at the pier (Figure 3B). Note that the depth of scour hole at the pier was calculated at specified time intervals. To appropriately monitor drastic variations in scour depth with time, data was recorded at short time intervals (2 minutes, 5 minutes and 10 minutes) for a period of 8 hours. Also, to determine longitudinal and lateral changes of scour depth in the vicinity of bridge piers, all bed profiles were recorded using a digital level gauge. A hydraulic jack was used to regulate the flume longitudinal slope, as illustrated in Figure 3.

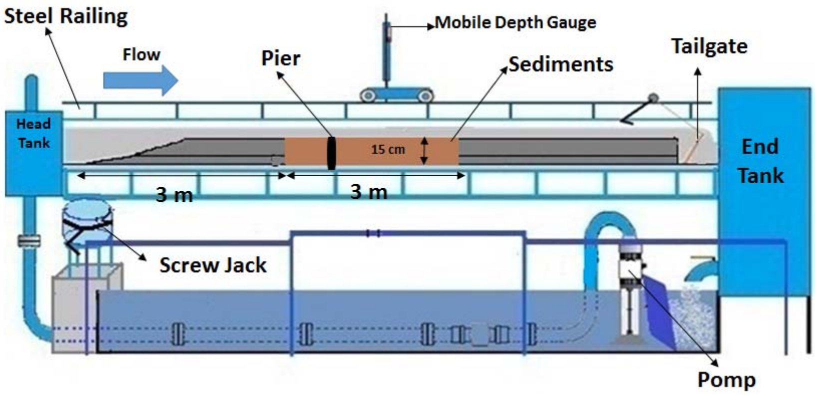

Figure (1): Sketch of the flume and its components

Figure (2): Frequency-adjusting device used to control flow rate

A B C

Figure (3): A. Channel used in experiment; B. Digital level gauge; C. Hydraulic jack

To reduce fluctuations of water surface in the upstream of the structure and to measure the height of water accurately, a mesh grille was used at the flume inlet. To further avoid the possible influence of incoming flow on the piers, location of the structure was set far from the inlet.

Experimental Conditions

Unsteady Flow Experiments

Stepped hydrograph was designed and applied to the model by a frequency-controlled pump to simulate unsteady flow. In the experiments of unsteady flow, hydrographs were used to meet the base flow rate of 4 l/s, peak flow rates of 8, 12, 16 and 20 l/s, peak time of 30 minutes with an introduced time step size of 7.5 minutes, as seen in Figure 4.

Sediment Particles' Specifications

According to Chiew and Melville (1987), to prevent the effect of channel wall on scour, maximum pier diameter is considered to be 10% of the channel width. Furthermore, Raudkivi and Ettema (1983) recommended that the ratio of channel width to base diameter should be greater than 25.6. If D/d50 is calculated to be from 30 to 70, maximum scour depth is then obtained (Breusers et al., 1977). D and d50 stand for base diameter and particle mean diameter, respectively. To prevent the formation of ripple in the alluvial context of the channel and to avoid adhesion effect of sedimentary particles on the scour process, particle mean diameter shall be at least 0.7mm. Breusers and Raudkivi (1991) also concluded that if D/d50 is greater than 20-25, both the formation of ripple and the adhesion effect of particles on the scour depth can be prevented. Therefore, sand with a mean diameter of 9.0 mm was chosen in our experiment. In this case, the maximum scour depth could be obtained and ripple could be avoided, thus preventing the flow regime to become turbulent and ooze to flow upstream. With the transportation of sediments into the scour hole, scour depth decreases. The distribution of sediment particle sizes used in this paper is shown in Figure 5.

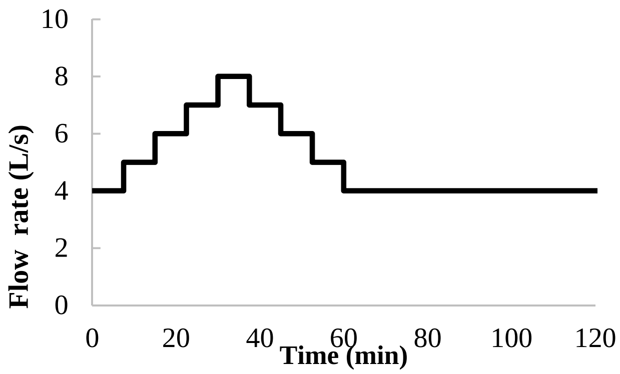

Figure (4): Triangular stepped hydrograph with peak flow rate of 8 l/s, a peak time of 30 min and a time step of 7.5 min

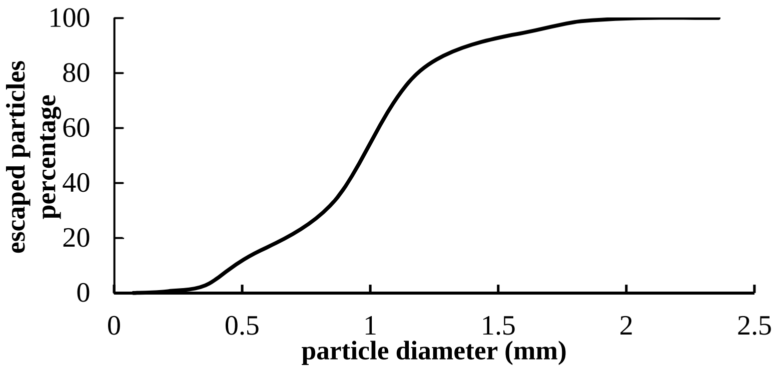

Figure (5): Sediment size curve

Experiment Equilibrium Time Determination

Chiew (1992) and Zarrati et al. (2004) determined the equilibrium time as a duration in which scour depth variation is less than 1mm in an 8 hour time interval. Melville and Chiew (1999) pointed out that equilibrium time depends on the base diameter. They suggested that if the scour depth variations are less than 5% of the base diameter over 24 hours, then equilibrium is achieved. Mia and Nago (2003) considered equilibrium as a time when scour depth variation is measured to be less than 1mm after a 1 hour time period. In this paper, the method suggested by Chiew (1992) was adopted. In order to determine the equilibrium time, an experiment was undertaken on a cylindrical pier in steady flow condition with the flow rate of 20 l/s and V/VC=0.94, for 48 hours; meanwhile, variations of scour depth were recorded during the experiment.

Experimental Procedure

After the installation of bridge piers at the desired location, the bed material was completely drained; then, sediment surface was perfectly aligned without pressing using a level gauge. Experiments were undertaken for two types: control experiments (sediments without nano-materials) and original experiments (sediments mixed with nano-materials). The experimental procedure is described as follows. Sediment in the vicinity of piers was taken and then weighed using a 35x25x10 cm^3 dimensioned mold. In addition to water, nano-clay material with 1% volume fraction was mixed with sand taken from the mold. Due to no soil compaction in the vicinity of bridge piers in control experiments, it was taken into consideration that original experiments involve nano-clays, which do not create any compaction. After sand mixed with nano-clay was cast, it became flat and no compaction was observed. Also, at a depth of 5cm from the surface per 1cm increase in level, nano-clay in layer form was poured on mold surface. Finally, in order to prevent sediment transport and sediment drainage in the vicinity of piers and nano-clay to agglomerate in the bottom parts, the flume was slowly filled with water up to 10cm. Then, after about 30 minutes, sediment was saturated, which was then to set flow rate and water surface to a pre-defined value.

Empirical Relationships for Estimating Maximum Scour Depth

Many empirical formulae have been proposed by various researchers to estimate the maximum scour depth on bridge piers in steady flow condition. Some of the empirical formulae are shown in Table 1, in which the parameters represent the following:

Fr_1: Flow Froude number.

Y: Depth of upstream flow.

D: Mean diameter.

Fr: Froude number.

K_θ and K_1: Coefficients related to the shape of the pier. The amount of K_θ for circle piers, aerodynamic piers and rectangular piers are 1, 0.7 and 1.3, respectively.

K_s and K_2: Coefficients which represent the crashing orientation of flow to the piers.

K_3: A coefficient which represents the bed conditions.

K_4: A coefficient which is used when forming a protective layer on a scour hole.

Table 1. Empirical formulae for estimating maximum scour depth used in this study

Formula	Researcher(s)
$\frac{y_s}{D} = 1.34\sqrt{\frac{y}{D}}$	Laursen and Toch (1956)
$\frac{y_s}{D} = 1.5\left(\frac{y}{D}\right)^{0.3}$	Neil (1964)
$\frac{y_s}{D} = 2.34\left(\frac{y}{D}\right)^{0.381} Fr_1^{0.619} y^{-0.06}$	Shen (1969)
$\frac{y_s}{D} = 2\tanh\left(\frac{y}{D}\right) K_S K_\theta$	Breusers (1977)
$\frac{y_s}{D} = 2K_1K_2K_3K_4\left(\frac{y_1}{D}\right)^{0.35} Fr_1^{0.43}$	Richardson and Davis (2001)
$y_s = 0.18 K_W K_S K_\theta \left(D\frac{V}{v}\right)^{0.6}$	Beriad et al. (2004)

To assess the accuracy of the results, two statistical indicators; *RMSE* and *MAE*, are used to represent Root Mean Square Error and Mean Absolute Error, respectively, as defined by :

$$RMSE = \sqrt{\frac{\sum(P_{abs} - P_{com})^2}{N}} \quad (1)$$

$$MAE = \frac{\sum\frac{|P_{abs} - P_{com}|}{P_{abs}} \times 100}{N} \quad (2)$$

where P_{abs} is a parameter measured in laboratory, P_{com} is a parameter obtained from an empirical formula and N represents the total number of data.

Characteristics of Nano-materials

Early studies on nano-technology applications in civil engineering were conducted in the 1990s. Any substance with at least one dimension in the nanometer scale (smaller than 100 nm) is referred to as nano-structure (Brock, 1997). Nano-technology offers the capability to produce materials, new tools and systems with control at the molecular and atomic level. Adding some additives to the soil is one of the effective methods to improve some soil characteristics, such as the relationship between stress and strain-strength, permeability and self-healing, especially in some geotechnical structures, e.g. embankment dams, road embankments, synthetic roofing and landfills. Unique features of nano-materials and their applications in other fields of science and engineering have led to fundamental changes, but little attention to this matter has been drawn into water engineering. Purity and cationic exchange capacity are considered as the two major strengthening attributes of nano-clays (Ghaffarpour Jahromi et al., 2011). By separating clay sheets from each other, nano-clay is created with a very active and large surface area. The large and active surface can result in a strong permanent interaction between nano-clay and its surroundings. In our experiment, a commercial nano-clay was used, referred to as CLOISITE-15A with its characteristics shown in Table. 2. The nano-clay is in the form of white powder, as seen in Figure 6.

Table 2. Characteristics of nano-clay used in this study

Name	CLOISITE-15A
Organic salts	MT2EtOH
Substance	Mount Morionite
Anion	Chloride
Special level	$9400m^{2/g}$
XRD	*d'=31.5Å*
Plastic limit	88.2
Interstitial water	> 2%
Weight loss due to burning	30%
10% diameter	> 2μm
50% diameter	> 6μm
90% diameter	> 13μm

Figure (6): Sample of nano-clay used in this study

RESULTS AND DISCUSSION

Maximum Scour Depth Estimation in Steady Flow Condition

To estimate the scour depth at the pier, we compared experimental data of relative maximum scour depth in steady flow condition in control experiments with the empirical formulae given in Table 1, as illustrated in Figure 7. The results predicted by the formula obtained by Briaud et al. (2004) are most consistent with the experimental data, but some deficiency exists, with an error of about 13% at low flow rates and the accuracy is improved at high flow rates. Due to the critical process of pier scour at high flow conditions (flood), it is not surprising that the formula of Briaud et al. (2004) gives a better accuracy at high flow rates. Among those compared formulae, Laursen and Toch's (1956) formula has the largest errors with RMSE and MAE being about 0.778 and 51.4%, respectively, whereas the formula proposed by Briaud et al. (2004) is the most accurate, with RMSE and MAE being about 0.135 and 8.2%, respectively.

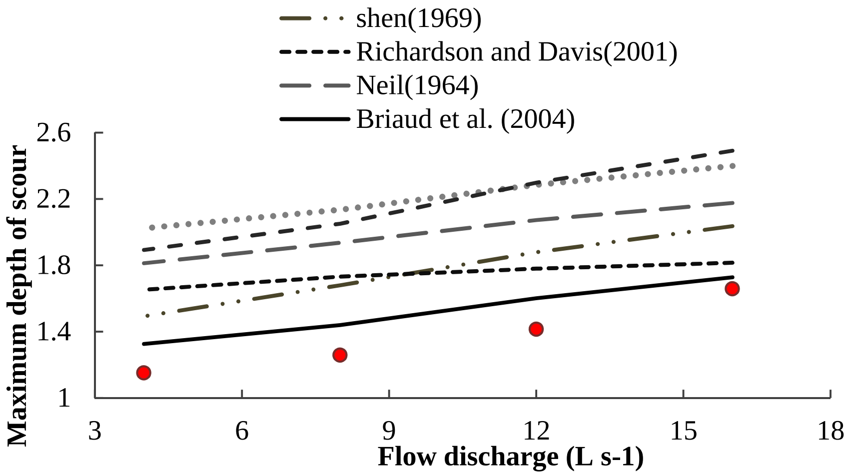

Figure (7): **Comparison of scour maximum depth estimation between the formulae and experimental data in steady flow condition in control experiments**

Maximum Scour Depth in Steady and Unsteady Flows

Table 3 shows the experimental data of maximum scour depth in both steady and unsteady flow conditions (with a base flow rate of 4 l/s and peak flow rates of 8, 12, 16 and 20 l/s and a peak time of 30 minutes at a time step size of 5.7 minutes) with no nano-clay material (control experiments).

The experimental data in original experiments (with the use of nano-clay material) is given in Table 4, where Froude number is calculated at the peak flow rate. Table 4 shows that maximum depth of scour for different flow rates in steady flow is 25% higher than that in unsteady flow condition. By comparing the maximum scour depth in both steady and unsteady flow conditions in control experiments and original experiments, it is observed that with the utilization of nanostructured materials, the scour depth is reduced 37% to 64% and 32% to 47% for steady and unsteady flows, respectively. Table 5 provides the percent of maximum scour depth reduction by using nano-clay material in the vicinity of the bridge piers.

Scour depth reduction in unsteady flow condition is higher than that in steady flow condition. Scour depth reduction is around 41% to 52% and around 56% to 62%, in steady and unsteady flow conditions, respectively.

Table 3. Maximum scour depth in steady and unsteady flows in control experiments

Maximum scour depth(mm)		$Fr = \frac{U}{\sqrt{gy}}$	Flow rate (l/s)
Unsteady flow	Steady flow		
-	37.60	0.25	4
32.5	44.03	0.29	8
37.4	49.50	0.33	12
43	58.03	0.36	16
47.4	64.50	0.39	20

Table 4. Maximum scour depth in steady and unsteady flows in original experiments

Maximum scour depth (mm)		$Fr = \frac{U}{\sqrt{gy}}$	Flow rate (l/s)
Unsteady flow	Steady flow		
-	21.98	0.25	4
14	25.73	0.29	8
15.5	26.08	0.33	12
16.03	27.76	0.36	16
17.6	36.01	0.39	20

Table 5. Percentage of decrease in maximum scour depth using nano-clay in comparison with control experiments

Maximum scour depth (mm)		$Fr = \frac{U}{\sqrt{gy}}$	Flow rate (l/s)
Unsteady flow	Steady flow		
-	41.54	0.25	4
56.15	41.56	0.29	8
57.75	47.30	0.33	12
59.53	52.16	0.36	16
62.86	44.23	0.39	20

To better understand the change of scour depth, Figure 8 shows time variations of the scour depth reduction due to utilization of nano-clay materials in all flow rates.

Figure 8 clearly shows that the largest reduction in scour depth occurs at maximum flow rate (i.e., 20 l/s). The greatest reduction in the flow rate was recorded to be around 88% at the beginning of the experiment and the lowest amount was recorded to be around 63% at the end of the experiment (equilibrium conditions of the test). The minimum effect of using nano-clay material was at the lowest flow rate (i.e., 8 l/s) which was obtained to be around 56%. Presence of nano-clay material is more effective in controlling local scour in the first minutes and the effect is gradually reduced when approaching the equilibrium time.

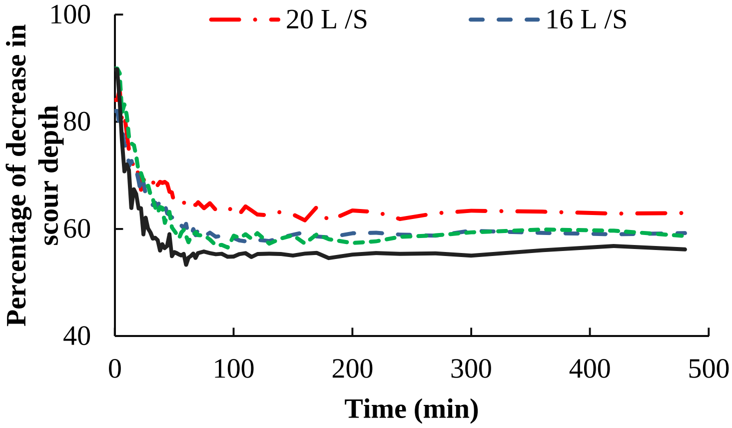

Figure (8): Time variation regarding the percentage of decrease in scour depth using nano-clays in unsteady flow

Time Development of Scour Depth

Figure 9 shows time variation of scour depth at the base of the pier at four different flow rates in the control experiments. The vertical axis is the ratio of maximum scour depth (ds) to base diameter (D) and the horizontal axis is the ratio of required time (t) to the entire time of the experiment (te). For all flow rates, the rate of variation in scour depth reduces as time passes, until it is at the lowest in equilibrium time. Furthermore, the maximum scour depth increases with increasing flow rate. The same results for the original experiments are illustrated in Figure 10, where the process of scour variation is almost the same as that not using the nano-clay material and the maximum scour depth also increases with increasing flow rate. Interestingly, using nano-clay material led to an effective control of maximum scour depth, so the relative scour depth can be constant in all flow rates. This result shows that the use of nano-clay materials can strengthen the structure of soil layers around bridge piers and scour depth has little variation even with increasing the flow rate (from 8 to 20 l/s) which will increase the shear stress. The results of Figures 9 and 10 also show that by increasing the flow rate from 4 l/s to 8 l/s, the relative scour depth is increased, demonstrating the slight effect of utilizing nano-clay material on scour depth reduction.

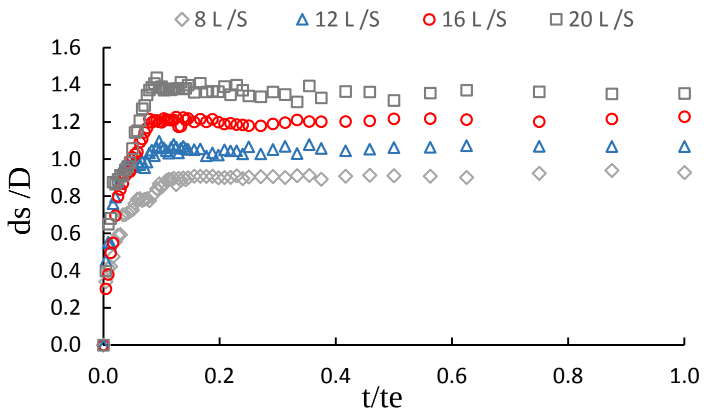

Figure (9): Time variation of scour depth in the vicinity of bridge piers in control experiments and unsteady flow condition

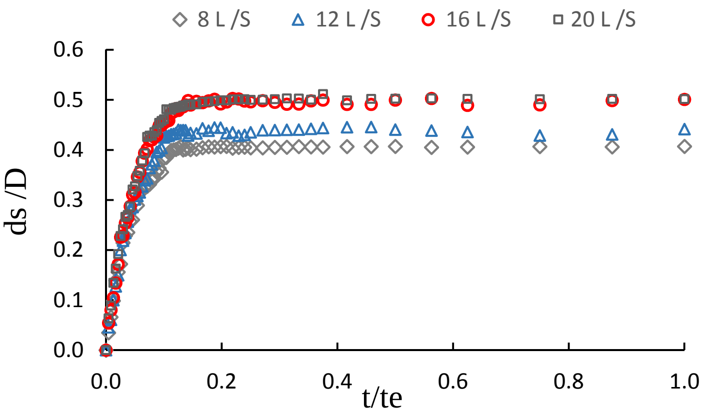

Figure (10): Time variation of scour depth in the vicinity of bridge piers in original experiments and unsteady flow condition

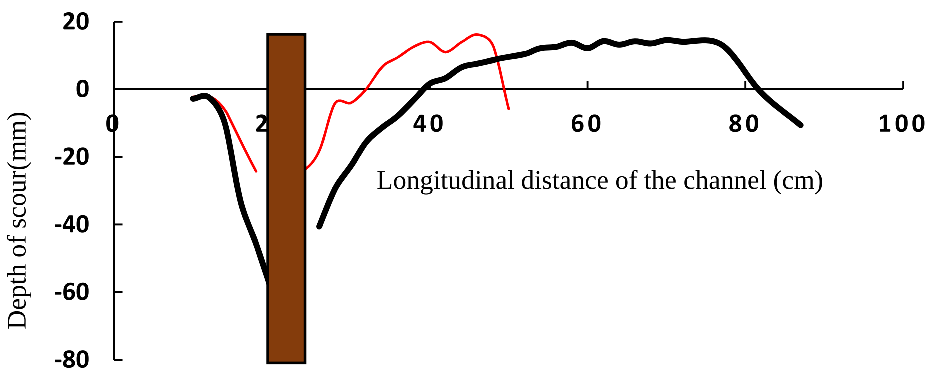

Figure (11): Comparison between scour depth profiles in control and original experiments at A flow rate of 20 L/s

Figure (12): A view of scour hole protected by nano-clay material

Figure 11 shows the scour depth profile of channel bed in both control and original experiments at the maximum flow rate (i.e., 20 l/s). It is shown that with the use of nano-clay materials, scour depth has decreased from around 47 mm to around 18 mm. Figure 12 shows the location of scour cavity in the equilibrium status of these experiments. It clearly shows that the white layer of nano-clay material protects bridge piers from scour.

CONCLUSIONS

Through experimental study, we examined the effect of utilizing nano-clay material in reducing maximum scour depth at bridge piers in steady and unsteady flows in sub-critical and clear water scour conditions. A few points can be drawn as follows: The experimental results of using nano-clay material with concentration of 1% and at four different flow rates indicated that the effect of nano-clay material in reducing maximum scour depth increases as the flow rate increases. At the flow rate (20 l/s), a decrease in maximum scour depth is observed as compared with that of not utilizing nano-clay material. The maximum scour depth has decreased from 48 mm to 17 mm; i.e., a 63% decrease in unsteady flow and a 23.44% decrease in steady flow conditions. Even at minimum flow rate (8 l/s), the effect of utilization of nano-clay material in reducing maximum scour depth was found to be 56% at unsteady flow and 41.6% at steady flow, respectively.

These results has demonstrated the nano-clay material role in controlling the scour, especially in syllabic flow rates which are the most critical conditions for extreme scour at bridges. Due to the fact that nano-clay materials are made of soil, these materials are environmentally compatible with the river, so they have great potential application in ecosystem protection. It is also expected that by increasing the concentration of nano-clay material in waterways, the maximum scour depth of hydraulic structures can be further reduced.

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