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The Impact of Foundation Scour on The Behaviour of A Bridge Pier

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ABSTRACT

The response of the bridge to the assessment of flood damage is constrained by a restricted examination of soil-specific vulnerabilities and the hydrodynamic forces linked to local scour. The research study will, consequently, aim to address these knowledge gaps in assessing the structural susceptibility of bridges to flooding in very stiff clay (type B) and medium dense sand (type C) soil. This research aims to analyse the behaviour and response of the bridge model when subjected to varying depths of local scour across different soil types. To accomplish this objective, a three-dimensional numerical model is employed for a standard three-span reinforced concrete bridge. In the conducted experiment, a total of 192 scenarios were simulated, considering four distinct levels of local scour depth across two different soil types. The analytical results indicated a notable increase in pier displacement because of the augmented scour depth. The recorded displacement in medium dense sand exhibited a 42 percent increase because of the rise in scour depth. Consequently, it was determined that the impact of erosion caused by flooding on bridges spanning rivers must be accounted for when designing the bridge's foundation.

Keywords: Scour depth; displacement; water level; velocities; foundation

INTRODUCTION

The importance of bridges within transportation infrastructure and the global economy has brought about the need to ensure that their performance objectives are met. Satisfaction of the requirements prescribed by modern bridge design standards entails an essential use of accurate modelling tools and detailed assessment of vulnerabilities to natural hazards. The primary factors contributing to bridge failure, along with their associated impacts on the operational transportation system, are linked to local scour, channel migration, and loads induced by flooding, all of which pertain to hydraulic phenomena (Kosič et al. 2023). Zhenhao (2023) elucidates that scour constitutes the primary cause of bridge collapses in the United States from 1980 to 2012, surpassing other contributing factors and accounting for more than 50% of such incidents. Furthermore, changes in climate and global warming have caused floods to be more frequent, whereas their predictability is increasingly complicated to forecast in recent decades (Anisha et al. 2022). The catastrophic floods that affected western Europe this July 2021 showed the scale of the devastation incurred. The repercussions have been significant in Germany, Belgium, and the Netherlands, marked by substantial loss of life and devastation of residential properties. The communication networks, along with other critical services, have experienced significant failures. These nations have made substantial investments in the advancement of early warning systems and flood mitigation strategies in comparison to the majority of other regions globally (Cornwall, 2021; Loli et al. 2022).

A considerable number of researchers concentrate on the evaluation of seismic hazards in the context of bridge design, often neglecting the necessity for a thorough assessment of the probability that bridges may exceed their damage threshold due to hydrodynamic forces and scour associated with flood hazards (Anisha et al. 2022; Argyroudis et al. 2021; Swagata et al. 2011). There is, therefore, a direct need for an appropriate method to analyse the flood risk, specifically with regard to the erosion and hydrodynamic actions on the bridge structures. Most of the studies related to the resilience of transport infrastructures are rather limited, especially those concerning the impacts caused by flooding and serious erosion. Considering that fact, further research for overall checking regarding resilience and structural integrities is highly necessary for the most unpredictable environmental or geological hazards for flood hazard loads, which may alter its bridge-behaviour resistance and magnitude of potential hazard variables, is huge, and an overall unpredictable variable check is essential to be performed.

This study highlights the crucial need to prioritize the safety and dependability of roadway bridges, particularly in considering rising flood levels and scour depth. This research emphasizes the importance of considering soil-structure interaction in bridge design by examining how bridge respond in different types of soil condition which are very stiff clay and medium dense sand. The gained insights have the potential to improve engineering practices, resulting in bridges that are more resilient and tailored to their specific environments. This, in turn can enhance public safety by reducing the risk of structural failures during extreme flood events.

SCOUR MECHANISM

Bridge scour is often cited as a major cause of bridge failure under flooding conditions. During a flood, a significant surge in water velocity occurs as it flows downstream. Figure 1 illustrates this phenomenon, which transfers water from the surface to the bottom around bridge piers. The downward movement of water displaces sediments around the foundations, resulting in the formation of a scour hole. Fluctuations in flow depths cause the horseshoe and wake vortex to form. This event caused the formation of a scour hole with a specific depth (Arneson et al. 2012).

Bridge scour, the erosion of sediment around bridge foundations, is a common occurrence. Figure 2 depicts a transverse cross section of the bridge, showing both the presence and absence of scouring (Anisha et al. 2022). The process of soil erosion around bridge piers and foundations results in the exposure of the foundation, which subsequently diminishes the soil's ability to provide strength and stiffness (Kim et al. 2017). This occurrence has led to an elongation of the foundation without support, a decrease in the sideways rigidity, strength, resistance to buckling, and safety factor against stability, and an increased susceptibility of the overall bridge structure.

There is a serious shortage in research regarding the resilience of transport infrastructure in relation to flooding, severe erosion, and seismic pressure. Further research is required to have a complete evaluation of bridge durability and stability, especially in respect to sudden environmental and geological hazards. This study covers, in particular, how flood events—most especially hydrodynamic forces—affect the structural response of bridges because of flood-induced scour. The emphasis is on understanding the immediate consequences of these events.

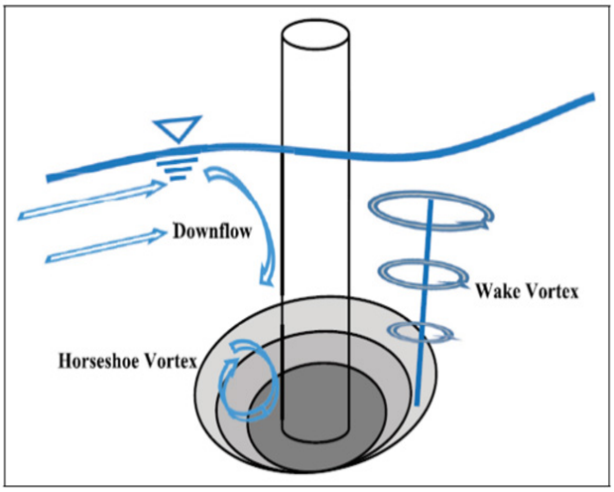


FIGURE 1. Occurrence of scour hole during flood (Kim et al, 2017).

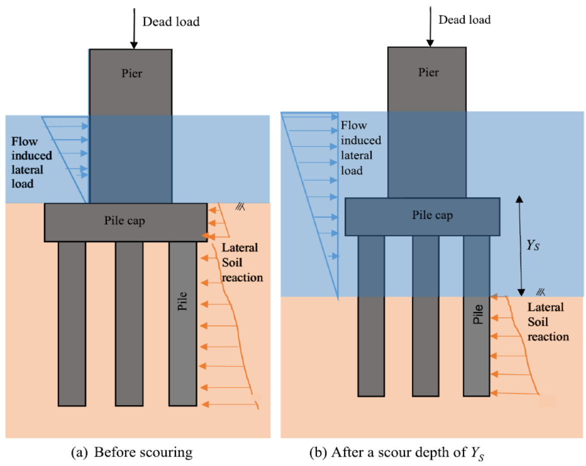
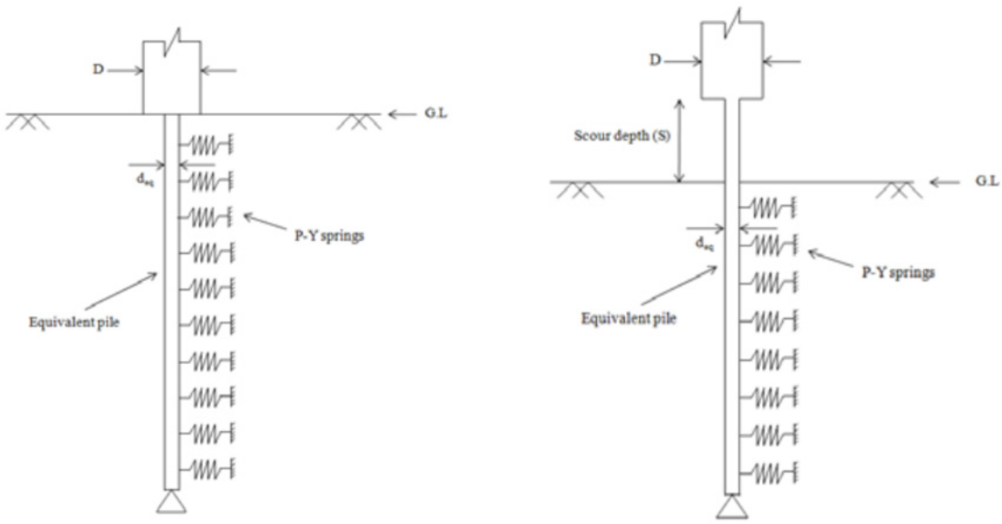


FIGURE 2. Influence of scour on stability of pier foundation (Anisha et al, 2022).

According to Argyroudis & Mitoulis (2021), the interaction between water-soil and the bridge is an important factor in comprehending the failure modes of flood-critical bridges. The bridge components may be affected, including the foundation being vulnerable to scouring and hydraulic forces impacting the footing, pier, and/or depth of water may cause it to overflow onto the deck, resulting in considerable hydraulic forces on the superstructure. These effects are widely recognised as fundamental.

P-Y SPRING

In numerical modelling, the interaction between the soil, the foundation, and the structure is simulated by means of P-y springs, which have nonlinear behaviour along the entire length of the pile under consideration (Swagata et al, 2011). Figure 3a illustrates the interaction between soil and pile in the absence of scour. Nonlinear spring's load-deflection curves, which are P-y curves, are generated for every 1.2-meter interval corresponding to the depth of the analogous pile. Scour-induced loss of lateral support is simulated by the removal of P-y springs at the depth of scour as shown in Figure 3b. Hinge connections are observed at both ends of the individual piles. This concept is used to evaluate the bridge response in case scour takes place around the bridge piers, which allows for an investigation of the soil-pile interaction regarding the scour phenomenon.



Soil-pile interaction without scour

Soil-pile interaction with scour

FIGURE 3. Soil structure interaction (Swagata et al, 2011).

MATERIALS AND METHODS

For the flood hazard, eight (8) flood velocity recorded on very stiff clay and medium dense sand are selected for the analysis. In this study, the scour depth and flood water level served as the intensity measure (IM) for assessing the flood hazard. The velocity of the flood was equal to 2, 4, 6, 8, 10, 12, 14, and 16 m/s (critical velocity, Vc) and was applied individually for each scour depth, which are 0Df, 1Df, 1.5Df, and 2Df, to simulate the sequential onset of the two risks. The foundation depth (Df) is 1.2 metres, and scouring is expected to happen when the floodwater level exceeds one metre above ground level (riverbed level). Hence, a comprehensive examination was conducted on a total of 192 analyses, comprising 4 different Scour levels, 3 flood levels (4m, 5m and 7m), 8 flood velocities, and 2 soil conditions very stiff clay (ground type B) and medium dense sand (ground type C).

NUMERICAL MODELING

The present paper presents the material and geometrical information on the basis of available construction data. The data is taken from a retrofitting project that was executed. The bridge has a total of three main spans of 18 meters each, supported by two piers firmly anchored into the riverbed of the Langat River. The bridge has dimensions of 54 meters in length and 13 meters in breadth. The bridge has two traffic lanes with a width of 3.5 meters and is flanked by road shoulders on either side measuring 3 meters each. The bridge has cantilever beams at the upstream side that support it. Abutments on the bridge are 11 meters in the vertical dimension, while the footing has a horizontal dimension of 1 meter and extends along a distance of 5.5 meters. The piers are cylindrical in shape, 1.2 meters in diameter and 8 meters in height. Figure 4 shows the schematic diagram of the side elevation and the plan of the bridge.

The mechanical properties of the superstructure were obtained by destructive tests carried out as part of a retrofitting effort for the structure. Eurocode 2 specifies that the projected concrete quality of the bridge deck is equal to C25/30. The material model of the bridge is characterised as linear elastic. The bridge demonstrates a non-permeable characteristic. The study utilised ground types B (very stiff clay) and C (medium dense sand) as described by Eurocode 8 - Part 1. The simulation runs were extended to incorporate two distinct soil conditions and a total of 96 simulation runs were conducted for each soil type. The comprehensive approach resulted in a total of 192 simulation runs, allowing for a thorough analysis of the bridge's susceptibility to different environmental conditions, including varying flood water levels and scour depths. This approach captures a wide range of scenarios that accurately reflect real-life flood events. The bridge model depicted in Figure 5 was generated using the CSI Bridge programme. The construction of this bridge utilises reinforced concrete, with material qualities including a Poisson's Ratio of 0.2 and a Young's Modulus of 3 x 10^7 kN/m^2.

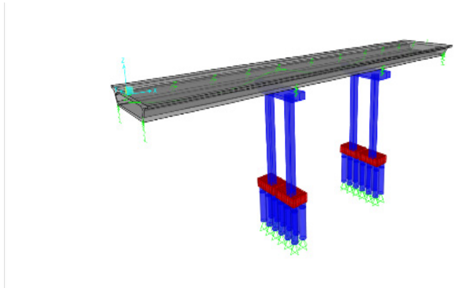


FIGURE 5. Bridge model in CSI Bridge.

For modelling soil-structure interaction (SSI), the p-y link element is a widely used tool in geotechnical engineering and finite element analysis software. It is utilised to accurately model the lateral SSI in the analysis of deep foundation system, like piles (Akram Zaky et al, 2020). In order to, simulate the decrease in lateral support, the p-y springs are eliminated until a depth of scour is reached, which is measured from the top of the comparable pile or ground surface. Figure 6 shows the piles that have been assigned with the p-y link.

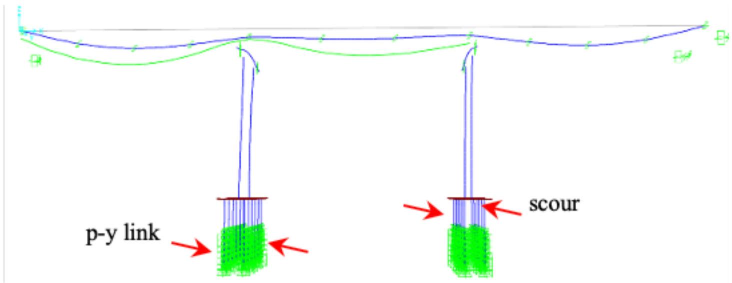


FIGURE 6. P-y spring and scour depth assigned.

RESULTS AND DISCUSSION

This study conducts a scour sensitivity analysis under floods around bridge piers. Most notably, these research findings stress the importance of understanding various hydrodynamic effects and local scouring conditions that control the stability of a roadway bridge. Accordingly, this paper is organised to address bridge pier responses subjected to various flooding velocities, scour depths, and soil types; additionally, a thorough analysis of the parameters affecting pier movement is undertaken.

EFFECT OF SCOUR DEPTH ON PIER DISPLACEMENT AT VARIOUS VELOCITY OF FLOOD

Figure 7 shows graphs of the relationship between scour depth and pier displacement, accounting for various flood velocities and flood water levels in a very stiff clay and medium dense sand soil condition. The graphs clearly demonstrate that as the scour depth increases, so does the displacement of the bridge pier. The trend remains consistent across various velocities and flood levels.

The primary observation from all the graphs is the clear trend that as the scour depth (S/D ratio) (S = scour depth; D = pier diameter) increases, the displacement of the bridge pier also increases for all tested velocities. This pattern holds true for both very stiff clay and medium dense sand substrates. This indicates that as floodwaters erode the soil around the bridge piers, the structural integrity of the bridge is compromised, leading to greater displacements. Additionally, higher flood velocities generally result in more significant displacements. At a scour depth ratio of 2, the maximum displacement of the pier occurs at a flood velocity of 16 m/s for both soil types. This trend shows the large influence of flood velocity on the stability of bridge piers, which is consistent with the aim of assessing bridge behaviour in view of rising flood levels. As indicated by Anisha et al. (2022), the scouring phenomenon around the bridge pier and its foundation leads to the exposure of the foundation, reducing the contribution of strength and stiffness of the soil. This leads to an increase in the unsupported length of the foundation, a decrease in lateral stiffness, strength, and buckling resistance, a reduced factor of safety against stability, as well as an increase in the vulnerability of the bridge. In addition, it was found that increased scour depth corresponds with a higher displacement value.

The displacement responses recorded under various local scour conditions indicate that medium dense sand, characterised by a reduced medium denseness compared with very stiff clay, will produce larger pier displacements for the same values of scour depth and velocity. This effect is more significant at larger values of scour depth, where the differences in displacements between the lower and higher velocities are more significant in medium dense sand than in very stiff clay. From the observation that the S/D = 2 for medium dense sand, at the same velocity, the displacement developed in this soil will be larger than in very stiff clay. It indicates that in the case of medium dense sand, the medium denseness that was adopted must be smaller in order to worsen the instability of a structure under hydrodynamic forces. This finding presents evidence in support of the need for better

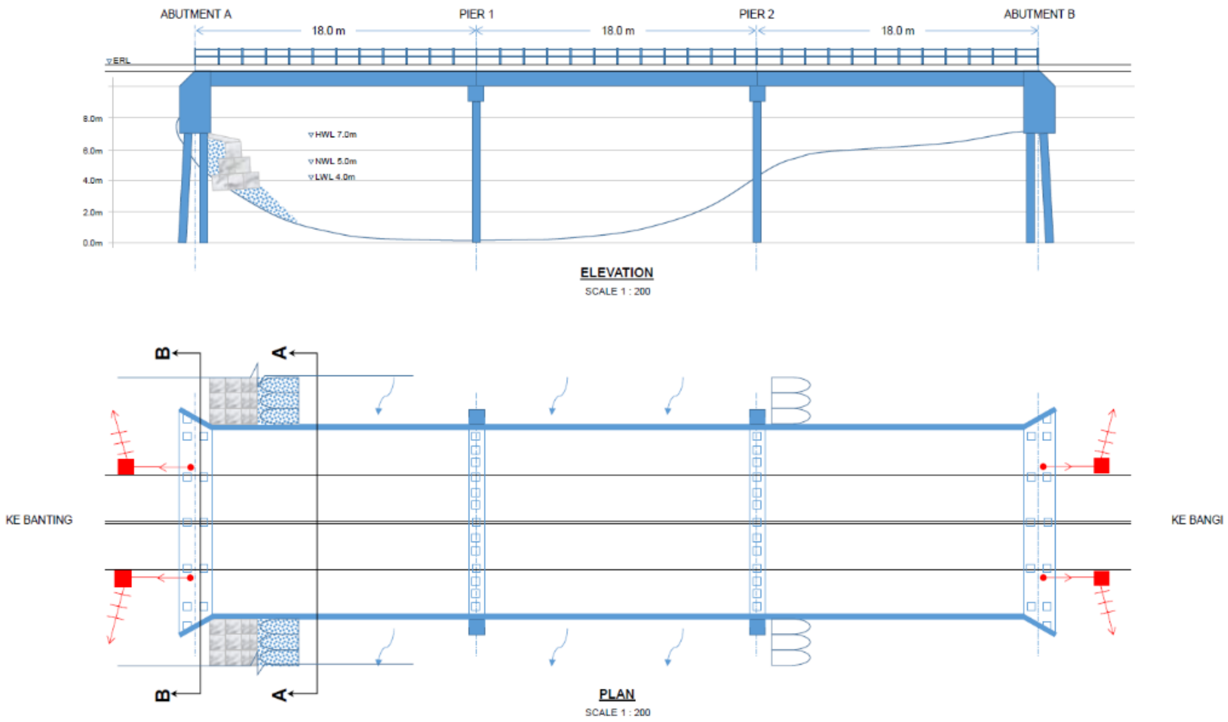


FIGURE 4. Dimension of the bridge.

engineering solutions in the design of bridges located in medium dense sand environments, which appear to be more prone to displacement due to the action of scour

EFFECT OF SOIL TYPE ON PIER DISPLACEMENT

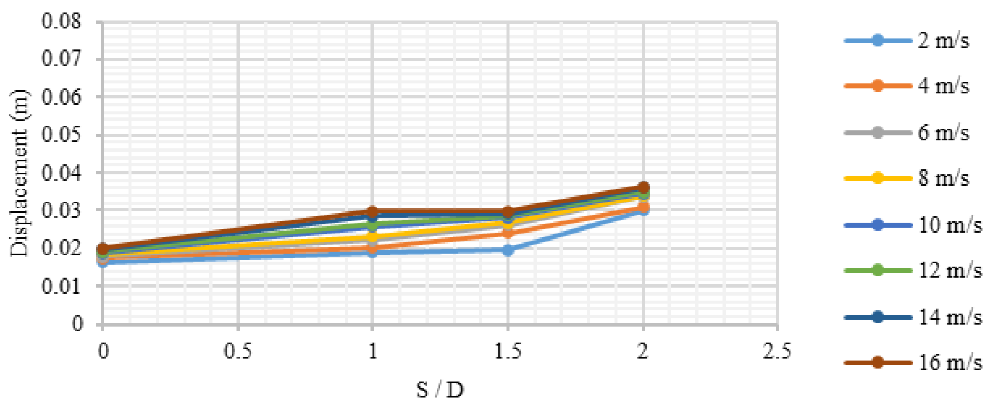
Figure 8 shows the detailed variations of maximum displacement of bridge pier with respect to various flood water levels according to different soil types and scour depths. Data have been divided into two main types of soils, which are very stiff clay and medium dense sand, into three different levels of flood water (4m, 5m, and 7m). It further considers four conditions of local scour, starting from no scour at 0df to severe scour conditions at 2df.

The graph shows that the maximum displacement of the pier increases in correspondence with the rise of flood water levels in both types of soil. For very stiff clay soil, the displacement changes from a moderate level at 4 meters to a considerably high value at 7 meters. Such a trend tends to indicate that a higher flood water level exerts higher hydrodynamic forces on the pier, which consequently increases the displacement. Similarly, in the case of medium dense sand soil, the displacement with an increase in flood water level also follows a similar pattern. Much higher displacements of medium dense sand at comparable water levels compared to those for very stiff clay show the large effects of soil types on the pier stability due to hydrodynamic action.

The phenomenon of local scour has a great impact on pier displacement, which is justified by a constant increase in the depth of scour that relates to higher displacements. Correspondingly, in both very stiff clay and medium dense sand soils, the maximum displacement remains rather small for no scour conditions (0df), whereas for a scour depth of 2df, it increases substantially. This increase in displacement emphasises that the pier is highly vulnerable to local scour, which affects the soil that supports the pier, leading to the increase in the displacements. It is very important to take into consideration the conditions of local scour during the design and construction of the piers of bridges in order to minimise the risk due to displacements. The results are also related to the pressure and deflection of the pier under extreme flood conditions. Chortis et al. (2020) have indicated that the soil pressures and pile deflections obtained from the numerical investigation distinctly show that the monopile exhibits a rigid response.

In an elaborated context, in all cases, rotation was imparted to the pile about the predetermined rotation point. Toe kick was thus demonstrated by developing high soil pressure at the toe of the pile while corresponding directional forces occurred in the top part of it. In fact, the change in displacement for different scour depths and profile types was directly affected by the variations in the stiffness and lateral load of the monopile significantly.

From the analysis of the difference in settlement between very stiff clay and medium dense sand soils, it can be obtained that piers in moderately dense sand are more susceptible to being displaced under the same hydrodynamic and scour conditions. At 7m flood water level and 2df scour depth, the displacement in medium dense sand is noticeably higher than in very stiff clay. This difference can be attributed to the inherent properties of sand, which is less medium dense and more prone to erosion compared to very stiff clay. Based on this study, bridges built on medium dense sand foundations require more robust design considerations to counteract the increased displacement and ensure structural stability.



(a) 4 meter of flood water level for very stiff clay soil.

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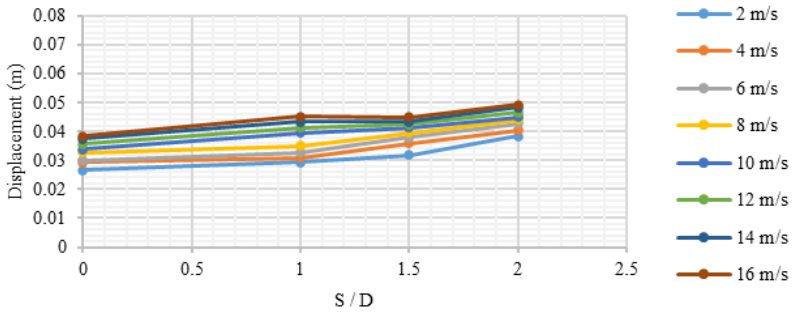
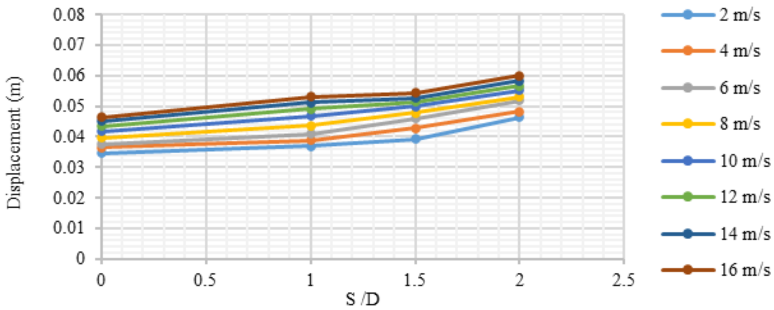
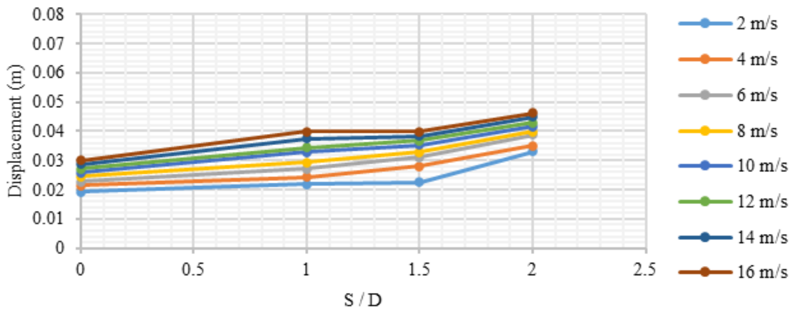


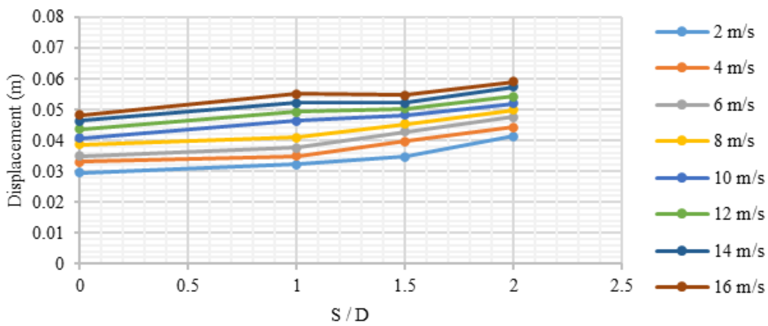
(b) 5 meter of flood water level for very stiff clay soil.



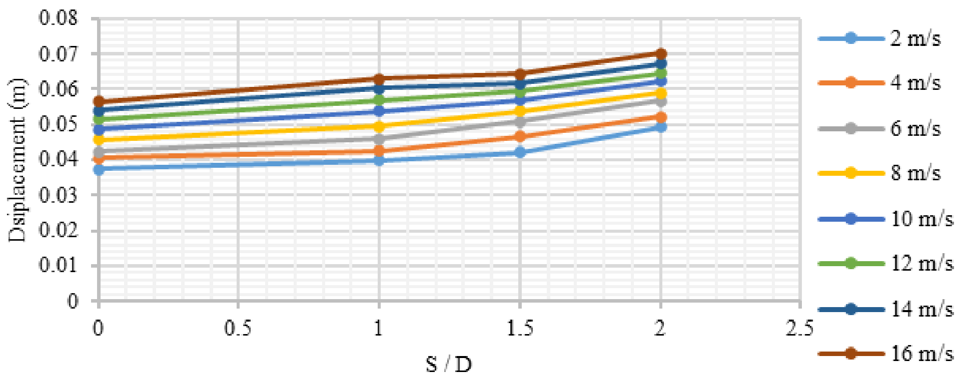
(c) 7 meter of flood water level for very stiff clay soil.



(d) 4 meter of flood water level for medium dense sand soil.



(e) 5 meter of flood water level for medium dense sand soil.



(f) 7 meter of flood water level for medium dense sand soil.

FIGURE 7. Graph of scour ratio versus pier displacement for every flood water level.

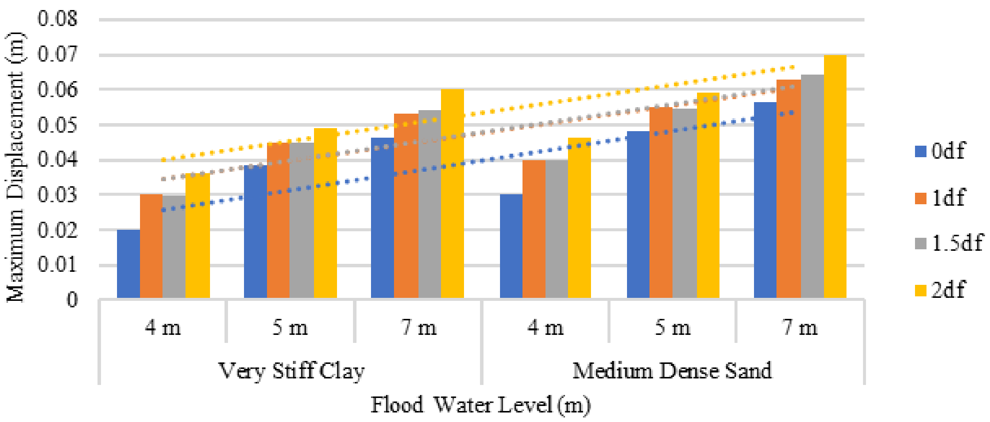


FIGURE 8. The effect of the soil conditions on maximum displacement of the pier.

CONCLUSION

Analysing the scour depths on pier displacement reveals that the trend remains consistent across various velocities and flood levels. Regardless of the flood velocity, increased scour depth leads to greater pier displacement, emphasizing the critical role of scour depth in structural stability. Notably, medium dense sand foundations show higher displacements than very stiff clay at the same scour depths and velocities, highlighting the need for more robust engineering solutions for bridges on medium dense sand soils. The consistency of this pattern underscores the compounded risk posed by flooding and scour on bridge integrity.

The effect of soil type on pier displacement further emphasizes the differences between very stiff clay and medium dense sand. Displacement increases with rising flood water levels for both soil types, with medium dense sand showing higher displacements, reinforcing the notion that medium dense sand is less stable under hydrodynamic effects. Additionally, increasing scour depths lead to greater displacements in both soil types, with medium dense sand showing more significant displacements. This underscores the vulnerability of piers to local scour, particularly in medium dense sand environments, and highlights the necessity for addressing local scour in bridge design and maintenance.

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DECLARATION OF COMPETING INTEREST

None.

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