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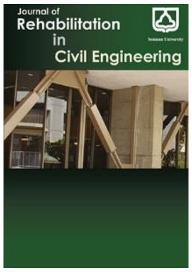

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Bridge Bed Strengthening, Disaster Prevention due to Scouring

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ABSTRACT

One of the major factors in deliberating the depth of foundations in structures adjacent to the water flow is the scouring phenomenon; the scouring is a phenomenon caused by the interactions between water flow and erodible bed materials, which causes the removal of sediments where hydraulic structures are located, including bridge piers. Every year, a great number of bridges are damaged as a result of local scoring of their piers and foundations. In this paper, the geotechnical study of Malahide viaduct failure due to scouring was carried out applying Plaxis 2D software. For this purpose, the Malahide viaduct, which was damaged in 2009 due to bed scouring of one of its piers, was selected and the necessary simulations were carried out in consonance with the bridge specifications, and the conditions of the bridge underlying bed was investigated. Simulations results revealed that the cause of scouring in the bed of collapsed pier was the high shear strains of the bed, bed shear strength parameters (i.e. angle of internal friction and cohesion) reduction and as a result, reducing the bed resistance to the scouring. Moreover, it was found that by using the micropile group below the foundation of bridge pier as a solution to reduce the scouring effect, the bed maximum scour depth is significantly reduced compared to the shallow foundations without micropiles; Furthermore, by using the micropile group, the shallow foundation thickness can be reduced, provided that after foundation thickness reduction and micropiles application, the structure safety factor remains in the stable range.

1. Introduction

Bridges are among the most important and widely used river structures and as the key to roadways, they are of great importance. Year by year, with the onset of flooding in each river, a large number of bridges are destroyed

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at a time when they are mostly needed. One of the major and effective factors causing these damages is the scouring phenomenon at the bed of piers and foundations. The scouring is a phenomenon caused by the interactions between water flow and erodible bed materials, which causes the removal of sediments where hydraulic structures are located, including pier foundations and bridge piers. This phenomenon results in erosion of the river bed and thereby, lowers its surface and causes the tendency to expose and damage of the structures on river route, such as bridge foundations and piles. The scouring can results in damages, structural overturning, financial losses and mortalities.

Deliberating the importance of scouring and its role in the design of the bridges and preventing this destructive phenomenon, it is clear that when designing the foundations, edges, organizing and temporary facilities of bridges in the river, estimating the rate of bed surface lowering in the vicinity of these structures as a result of scouring requires accurate examinations which necessitates accurate and comprehensive understanding of the flow pattern around the bridge pier and complete knowledge of the physics of the problem and the mechanism of the phenomenon. Understanding the types of scouring and the factors affecting its creation is indispensable for a study on the construction of bridges and buildings located in the river route. The foundations of bridge supports and piers should be placed under the maximum scouring level (maximum scour depth); otherwise, the bed of foundation will be removed and the bridge will collapse.

In recent years, various methods have been applied to reduce the scouring effect, including structural and hydraulic methods, and their efficiency in reducing the scouring effect has been confirmed: Ghorbani and Kells [1] Using submerged vanes at cylindrical piers, Moncada et al. [2] Using collars and slots in the bridge piers, Grimaldi et al. [3] Applying bed sill at downstream, Bozkus and Cesme [4] Using inclined piers, Debnath and Chaudhuri [5] The effect of suspended sediment concentration, Eghbali et al. [6] The effect of geometric parameters and foundation depth, Imamzadehei et al. [7] employing geotextile armored soil, Ardeshiri and Saneie [8] Using lozenge collar, Fael et al. [9] Effect of pier shape and pier alignment, Khan et al. [10] Effect of bridge pier scour pattern, Amini et al. [11] Applying collar; in the above-mentioned studies, the positive effect of various methods on reducing the scouring depth in hydraulic structures locations has been proven. However, the amount of these effects varies for different conditions and structures.

One of the usable methods to reduce the maximum scour depth below the bridges is using the micropile group below the piers foundation; through applying the micropile group below the bridge pier foundation, the shallow foundation thickness can be reduced. This thickness reduction along with micropiles should be taken into account such that the geotechnical stability of the structure is maintained; in other words, the structure safety factor should remain in the stable range after reducing the thickness of the pier foundation and application of micropiles underneath it [12]. Through using the micropile group below the foundation of bridge pier, the bed maximum scour depth could be reduced significantly compared to the shallow foundations without micropiles. As a result of the presence of micropiles in the flow path, the expansion of scour hole(s) decreases and bed materials removal could be significantly avoided. By applying the micropiles and placing them in the flow path, the flow energy applies more bearable on the bed, because a part of its energy depletes by micropiles, and the erosion of sediments due to the water flow decreases [12].

In this paper, the geotechnical study of Malahide viaduct failure due to scouring was carried out employing Plaxis 2D software. For this purpose, the Malahide viaduct, which was damaged in 2009 as a result of bed scouring of one of its piers, was selected and the necessary simulations were carried out in consonance with the bridge specifications, and the conditions of the bridge bed was investigated; Moreover , the solution to reduce the maximum scour depth of Malahide viaduct bed has been provided.

2. Research Method

For numerical simulations, a software pursuant to the Finite Element Method (FEM), Plaxis 2D was applied to model geotechnical simulations. A real bridge supported by shallow foundation that has been damaged by scouring with available geotechnical and hydraulic data, was the preliminary source of data for this research. To this end, the Malahide viaduct was selected. This bridge is located on the Broadmeadow Estuary, in the Republic of Ireland; this bridge was a communication route between Dublin and Belfast; Fig. 1 displays this bridge before its destruction.

Fig. 1. The Malahide viaduct [13].

The bridge consists of 12 spans supported by 11 piers and 2 supports at its both ends. The width of piers is 12 meters and their height are 2.5 meters. The structure of the Malahide viaduct is such that the piers are located on a concrete foundation along the bridge direction; the width of this foundation is 15 meters and its depth is 1.5 meters. The entire structure of the bridge is constructed on a permeable sandy embankment weir on the Estuary bed (The flow velocity of the Estuary is 4.19 m/s) [13]. Fig. 2 and Fig. 3 depict the bridge plan and pier No. 4 view from the angle along the bridge path and 3D view, respectively.

Table 1 illustrates the properties of concrete applied in the Malahide viaduct.

Table 1. The properties of concrete used in the Malahide viaduct [13].

Model	Linear Elastic
Type	Impermeable
γ_{unsat}	24 KN/m^3
γ_{sat}	-
k_x	-
k_y	-
E_{50}	2×10^7 KN/m^2
ν	۱۵.۰

Table 2 shows the properties of the permeable sandy embankment weir below the Malahide viaduct.

Table 2. The properties of the permeable sandy embankment weir below the Malahide viaduct [13].

Model	Mohr–Coulomb
Type	Drained
γ_{unsat}	17 KN/m^3
γ_{sat}	20 KN/m^3
k_x	1 m/day
k_y	1 m/day
E_{ref}	40000 KN/m^2
ν	3.0
c_{ref}	1 KN/m^2
ϕ	32°
ψ	2°
R_{int}	67.0

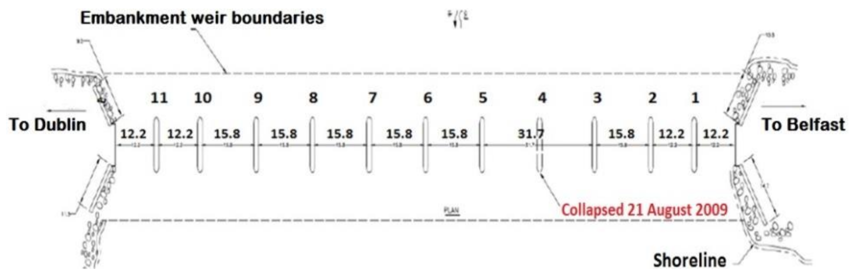


Fig. 2. The Malahide viaduct plan [13].

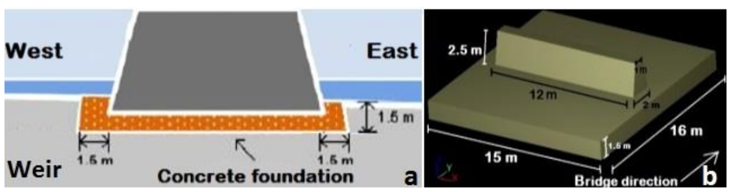


Fig. 3. Pier No. 4; a) View from the angle along the bridge path, b) 3D view [13]..

On August 21st 2009, Malahide viaduct was damaged as a result of collapse of pier No. 4 (from the Belfast side) and, consequently, the destruction of spans No. 4 and No. 5; the reason for this phenomenon was the scouring of bed materials between the spans No. 4 and No. 5, evacuation of the main part of bed materials under pier No. 4 and finally, the collapse of the pier and the spans supported by it [13]; this phenomenon is indicated in Fig. 4.

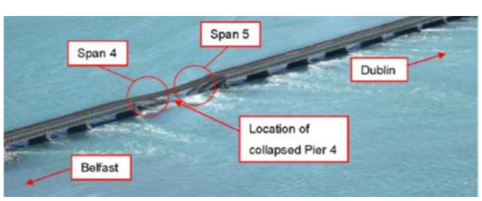


Fig. 4. The collapse of pier No. 4 in Malahide viaduct due to scouring [13].

3. Numerical Simulations and Analysis of Results

Plaxis 2D was applied for geotechnical simulations. The purpose of this simulation was the study of structural stability through the safety factor obtained from the software and examining the shear strains conditions of the bed.

3.1. Modeling and Materials Assigning

Fig. 5 reveals the modeled geometry of Malahide viaduct in Plaxis 2D software.

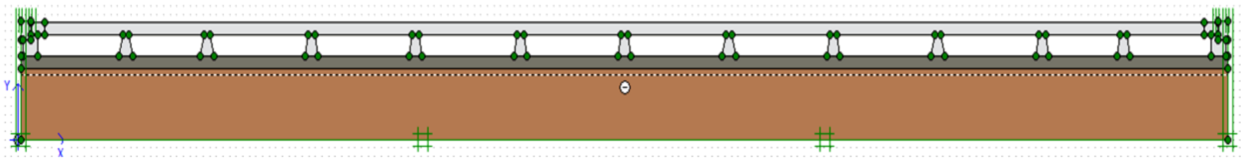


Fig. 5. The modeled geometry of Malahide viaduct in Plaxis 2D software.

The specifications of the bridge and bed materials were also defined into the software according to Tables (1) and (2).

The following items were considered for drawing the model:

- The interaction between the soil and the foundation was considered; thus, The R_{int} parameter (interface reduction factor) was applied in the sandy embankment weir properties; this parameter was obtained based on the resistance and the angle of internal friction of the soil, which is equal to 0.67 for sandy soils [14].
- The materials of the Malahide viaduct underlying bed are permeable (for drainage purposes), but the concrete used in the bridge structure is impermeable [13].
- In order to apply the boundary conditions, the "Standard Fixities Method" was used as the fastest and most appropriate method for applying the boundary conditions in geotechnical projects; these conditions were applied after the geometry modeling and assignment of materials and before generating the meshes (the green lines in Fig. 5). By applying the Standard Fixities Method, the vertical geometric lines are fixed in the horizontal direction at the points where the X-axis has the lowest and highest values (u_x=0); the horizontal geometric lines are completely fixed at the point where the Y-axis has the lowest value (u_x=u_y=0) and the extending plates over the boundaries, at the points those are defined on the model, cannot rotate (φ_z=0) [15]. These conditions were automatically applied on the model by Plaxis 2D software.

3.2. Meshes Generation

When the geometry model is complete, the finite element model (or mesh) can be generated. Plaxis 2D software allows for a fully automatic mesh generation procedure, in which the geometry is divided into elements of the basic element type and compatible structural elements, if applicable. The mesh generation takes full account of the position of points and lines in the geometry model, so that the exact position of layers, loads and structures is accounted for in the finite element mesh. The generation process is in consonance with a robust triangulation principle that searches for optimized triangles and which results in an unstructured mesh. Unstructured meshes are not formed from regular patterns of elements. The numerical performance of these meshes, however, is usually better than structured meshes with regular arrays of elements. In addition to the mesh generation itself, a transformation of input data (properties, boundary conditions, material sets, etc.) from the geometry model (points, lines and clusters) to the finite element mesh (elements, nodes and stress points) is made. In general, in the mesh generation of a model, it is note-worthy to mention that, in more important parts of the model, it is better to apply a finer meshing so that the software performs more sensitivity in performing the calculations in these parts and to be more accurate in the outputs [15]. In this research, in parts of the model where the stress concentration is higher, such as the lower parts of the foundation, finer meshes were generated. Fig. 6 displays the modeled geometry of the bridge in Plaxis 2D software pursuant to the generated meshes.

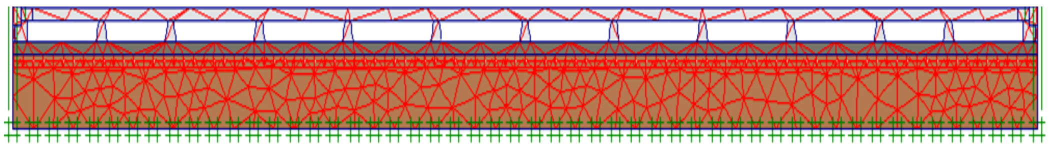


Fig. 6. The modeled geometry of the bridge in Plaxis 2D software along with the generated meshes.

3.3. Initial Conditions

Once the meshes were generated, the finite element model was complete. Before starting the calculations, however, the initial conditions should be generated. In general, the initial conditions comprise the initial groundwater conditions, the initial geometry configuration and the initial effective stress state [15]. In the initial conditions, it is assumed that the structure has not been constructed [15]; thus, in this research, the general model (the bridge and its piers) was eliminated and only the weir and the water flow were simulated; thus, the water stresses and weir weight were defined to Plaxis 2D software as the initial conditions.

3.4. Calculations

For more accurate calculations, the calculation process was divided into different phases. The phases were defined as "Staged Constructions" into Plaxis 2D software. In order to describe the process of project construction into the software, in addition to defining the initial conditions, it was necessary to define the construction phases to the software, respectively; so that the software would perform the analysis and calculations and provide the outputs for each phase; obviously, the results of the last phase are the general results of the model after its construction [15].

The computational phases were defined as follows:

1. **Activation of the bridge piers foundation:** In this phase, the mass of shallow foundation below the bridge piers was activated;
2. **Activation of bridge piers:** In this phase, in addition to bridge piers foundation, the bridge piers were also activated;
3. **Activation of bridge spans:** In this phase, by activating the spans confirming to the bridge piers, the geometry of the model was completed in order to perform the calculations.

3.5. Results and Discussions

After completing the simulation and performing the calculations by Plaxis 2D software, the software outputs were available; in the first step, in order to ensure the model stability, the total safety factor of the model was read. Fig. 7 portrays the calculations outputs after the simulation of the Malahide viaduct.

	Incremental multipliers		Total multipliers	
Prescribed displacements	Mdisp:	0.000	Σ-Mdisp:	1.000
Load system A	MloadA:	0.000	Σ-MloadA:	1.000
Load system B	MloadB:	0.000	Σ-MloadB:	1.000
Soil weight	Mweight:	0.000	Σ-Mweight:	1.000
Acceleration	Maccel:	0.000	Σ-Maccel:	0.000
Strength reduction factor	Msf:	0.000	Σ-Msf:	1.733
Time	Increment:	0.000	End time:	733.067
Dynamic time	Increment:	0.000	End time:	0.000

Fig. 7. The calculations outputs after the simulation of the Malahide viaduct.

In Fig. 7, the total safety factor of the model is represented by the "$\sum -Msf$", which is equal to 1.733 (i.e. S.F>1); therefore, the model was in a stable state and the reason for the Malahide viaduct failure could not be a structural weakness in a short term; rather this destruction has been caused by a time-dependent phenomenon. For a more complete review of the bridge conditions, the shear strains of the Malahide viaduct underlying bed were applied. Fig. 8 manifests the shear strains of the model.

According to Fig. 8, the shear strains conditions are approximately the same for the 7 middle piers, and the underlying bed of these piers has higher strains in comparison with the underlying bed of the 4 piers located at both ends of the bridge due to the exerted shear force. Philip and Rahimnejad [16] suggested that by reducing the soil shear strength parameters (i.e. angle of internal friction and cohesion), the shear deformations (shear strains) increase and the soil resistance to scouring is reduced; therefore, the underlying bed of the 7 middle piers, with higher shear strains, reveals less resistance against scouring compared to the underlying bed of the 4 piers located at both ends of the bridge. Considering the fact that the fourth pier to the right side of the model, which was destroyed by scouring in the actual sample, was among the 7 middle piers, it is evident that the cause of scouring in the bed of this pier and its collapse was the high shear strains of the bed, bed shear strength parameters (i.e. angle of internal friction and cohesion) reduction and as a result, reducing the bed resistance to the scouring; In fact, the underlying bed of the 7 middle piers had a greater tendency to scouring compared to the underlying bed of the 4 piers located at both ends of the bridge.

Due to the fact that the increased tension below the foundation of Malahide viaduct has been the reason of the local scouring, F.Marfavi [12] suggested the use of micropile group below the foundation of the bridge in order to eliminate the stress concentration and prevent the removing of the foundation underlying bed as a result of scouring. In his research, by reducing the shallow foundation thickness and using a micropile group to maintain the structural stability and improve the bed characteristics, preventing the expansion of scour holes and reducing the maximum scour depth were studied. Micropiles arrangement modeled beneath the foundation is as displayed in Fig. 9.

After conducting several experiments, Gomez et al. concluded that for obtaining a better bearing capacity by slender piles including micropiles, the distance between their heads should not be more than 1 meter 0. By applying 13 micropiles with a diameter of 25 centimeters and arranging their heads along the pier bottom line with a width of 12 meters, the distance between their heads will be 77 centimeters, which is an appropriate spacing for micropiles to maintain their bearing capacity. Pursuant to these interpretations, the micropiles arrangement modeled by F.Marfavi beneath the foundation is as exhibited in Fig. 9. [12].

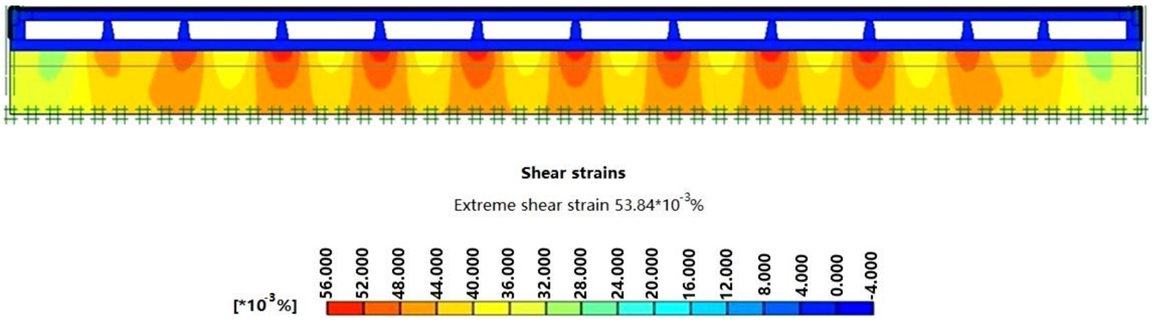


Fig. 8. The shear strains of the Malahide viaduct.

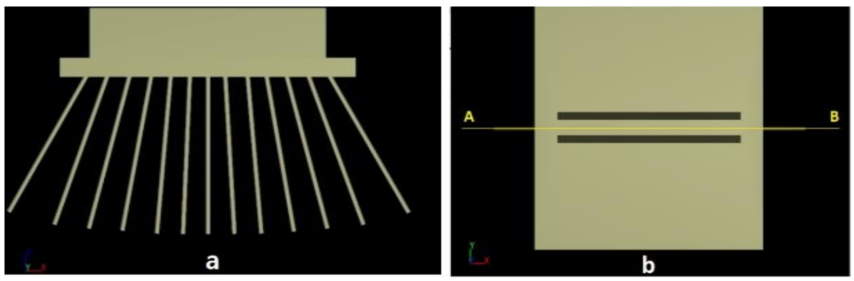


Fig. 9. Micropiles arrangement modeled beneath the foundation [12].
a) The gradual tilt of micropiles, b) The cross section AB corresponds to the arrangement direction of the head of micropile group.

The diameter proposed by Federal Highway Administration construction code (FHWA–SA–97–070) is 20 to 30 centimeters for micropiles embedded in saturated sandy soils 0; in F.Marfavi's simulation, the midpoint of this range (i.e. 25cm) was chosen as the diameter of micropiles [12].

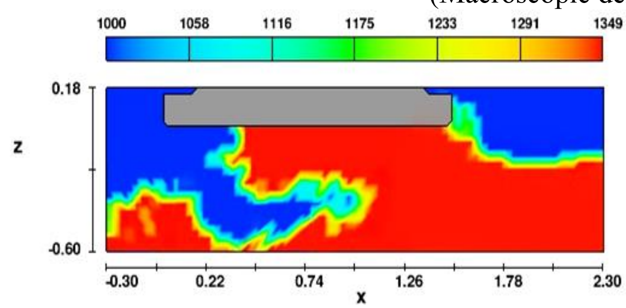
The chosen length of micropiles should not be less than a minimum value and more than a maximum value; on one side, this length should cover a depth more than the maximum scour depth, but this length should not be so high that would be detrimental to cost-effectiveness of the project. in F.Marfavi's simulation, the length of micropiles was selected to be 1.5 meters higher than the maximum scour depth obtained by him; i.e. 9 meters [12].

The micropiles must be angled so that they can act as a load bearing member, and also, they have to provide the full coverage for the scour hole; for this reason, among a micropile group, the middle micropiles were applied at a lower inclination angle, so that they could transfer the load exerted by the structure's weight into more depths, and the rest of micropiles were gradually sloped to provide a wider weir coverage to maintain a better soil resistance against scouring 0, [12].

F.Marfavi's simulations were performed in five stages by Plaxis 2D software (for geotechnical stability studies) and Flow 3D software (for hydraulic simulation). In the first two stages, the bridge with shallow foundation and without micropiles was simulated geotechnically and hydraulically, and the results were compared with bridge characteristics in the failure report reference. After ensuring the validity of the numerical model responses used, these stages were repeated for the bridge with reduced foundation thickness along with micropiles. In the fifth stage, the foundation with reduced thickness was simulated along with micropiles in the conditions of bed scouring in Plaxis 2D software. His results revealed that in case of using the micropile group below the foundation of bridge pier, the maximum scour depth of the bed is significantly reduced compared to the shallow foundation without micropiles. By applying the micropiles and placing them in the flow path, the flow energy is applied more bearable on the bed, because a part of its energy is depleted by micropiles, and the erosion of sediments due to the water flow is decreased; therefore, the expansion of scour hole(s) is decreased and bed materials removal is significantly avoided. In the parts of bed with more interactions with micropiles or in other words, in the parts where sediments are involved with micropiles, the lowest scouring occurred as a result of better preservation of sediments by micropiles against the flow path, and by getting farther from these parts, the preservation of the sediments is lowered and as a result, more scouring may occur. In addition to being a load bearing element and resistant element against settlement, micropiles also ameliorate the resistance profile of the surrounding soil including its cohesion due to cement slurry injection during their implementation, and by being placed against the water flow, they prevent the scouring of the bed sediments [12].

Fig. 10 and Table 3 portray the dimensions of created scour holes in the underlying bed of the Malahide viaduct collapsed pier, before and after the micropile group application. (The outputs were obtained by Flow 3D software; dimensions scale: 0.1 times the actual dimensions) Also, it was found that by applying the micropile group, the shallow foundation thickness can be reduced, provided that after foundation thickness reduction and micropiles application, the structure safety factor remains in the stable range [12].

(Macroscopic density contours)



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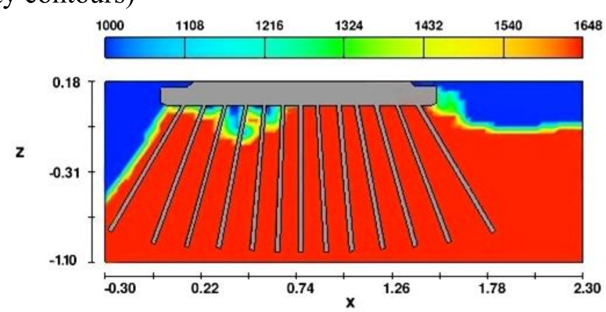

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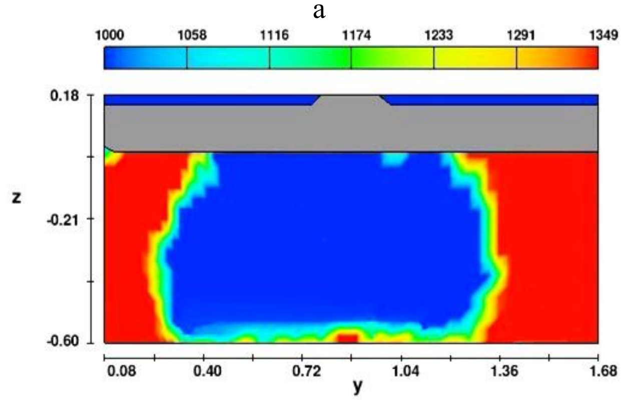

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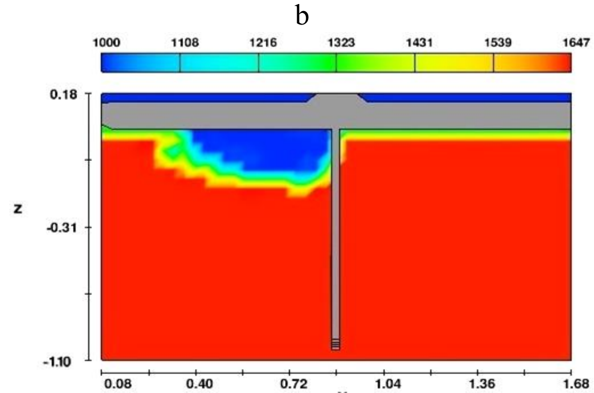

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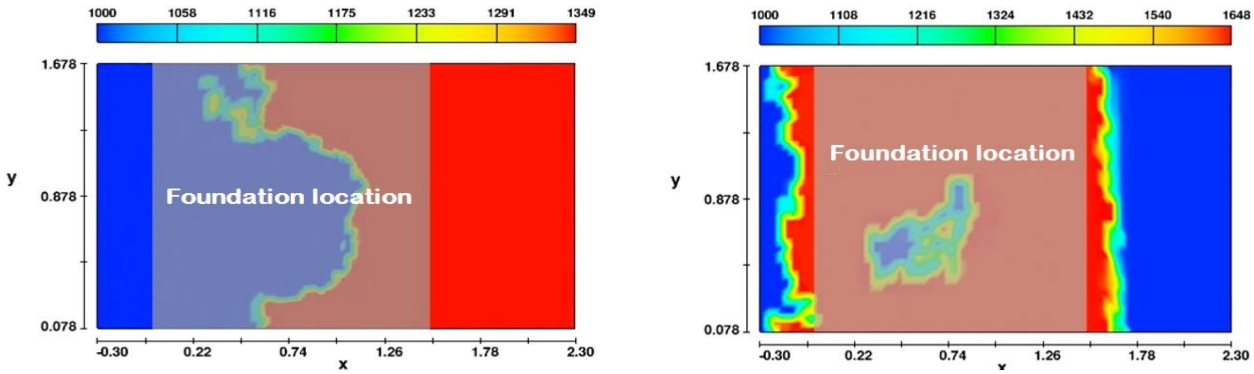

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Fig 10. The dimensions of created scour holes in the underlying bed of the Malahide viaduct collapsed pier, before and after the micropile group application [12].
a) Shallow foundation , b) The thickness-reduced foundation along with micropiles
c) Shallow foundation , d) The thickness-reduced foundation along with micropiles
e) Shallow foundation , f) The thickness-reduced foundation along with micropiles

Table 3. The dimensions of created scour hole below the foundation of Malahide viaduct collapsed pier, before and after the micropile group application [12].

	scour hole depth (m)	scour hole width (m)
Shallow foundation	7/5	11/2
The thickness-reduced foundation along with micropiles	3/38 □4/12 ↓□	5/6 □5/6 ↓□

4. Conclusion

After simulating the Malahide viaduct in Plaxis 2D software and observing the software outputs, the results revealed that the Malahide viaduct failure could not be a structural weakness in a short term; rather this destruction has been caused by a time-dependent phenomenon; since the total safety factor of the bridge was in the stable range. After studying the shear strains of the underlying bed of Malahide viaduct, it was observed that the shear strains conditions are approximately the same for the 7 middle piers, and the underlying bed of these piers has higher strains in comparison with the underlying bed of the 4 piers located at both ends of the bridge due to the exerted shear force; deliberated that by reducing the soil shear strength parameters (i.e. angle of internal friction and cohesion), the shear deformations (shear strains) increase and the soil resistance to scouring is reduced, the underlying bed of the 7 middle piers had a greater tendency to scouring compared to the underlying bed of the 4 piers located at both ends of the bridge; the pier which was collapsed by scouring in Malahide viaduct in 2009, was among these 7 middle piers.

Through applying the micropile group below the foundation of bridge pier as a solution to reduce the scouring effect, the bed maximum scour depth is significantly reduced compared to the shallow foundations without micropiles; by applying the micropiles and placing them in the flow path, the flow energy is applied more bearable on the bed, because a part of its energy is depleted by micropiles, and the erosion of sediments due to the water flow is decreased; therefore, the expansion of the scour hole(s) is decreased, and the major removal of the bed materials is avoided significantly. In the parts of bed with more interactions with micropiles or in other words, in the parts where sediments are involved with micropiles, the lowest scouring occurred due to better preservation of sediments by micropiles against the flow path, and by getting farther from these parts, the preservation of the sediments is lowered and as a result, more scouring may occur.

In addition to being a load bearing element and resistant element against settlement, micropiles also improve the resistance profile of the surrounding soil including its cohesion due to cement slurry injection during their implementation, and by being placed against the water flow, they prevent the scouring of the bed sediments.

Acknowledgments

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Notation

The following symbols are used in this paper:

γ_{unsat} = The unsaturated unit weight of the soil
γ_{sat} = The saturated unit weight of the soil
k_x = Horizontal permeability
k_y = Vertical permeability
E_{50}= Young's modulus
ν =Poisson's ratio
c_{ref} = Cohesion
ϕ = Angle of internal friction
ψ = Dilatancy angle
R_{int} = Interface reduction factor
u_x = Horizontal displacement
u_y = Vertical displacement
φ_z = Rotation angle
S.F = Safety factor
$\sum -Msf$ = Total safety factor

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