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Investigation of the effect of local scour on piled bridge foundation performance using the Hybrid Modelling Technique

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ABSTRACT: Scouring of piled foundations is a persistent hazard in bridge foundation design. The specific effect that scouring has on the stiffness and strength of such foundations is a source of significant uncertainty. The scour process is difficult to reproduce numerically, and the interaction between scouring, soil and structure is a complex phenomenon. This work describes the application of so-called "hybrid modelling technique" which is designed to address these issues by decoupling the hydraulic phenomenon from the investigation of the geotechnical performance. Real scoured soil profiles are produced in model tests, which are subsequently 3D scanned using a high-precision photogrammetry. Scan data is then processed and used to create a numerical calculation domain for finite element modelling. Model tests conducted using a specialised Miniaturised Tsunami Generator highlight in detail the scour patterns for single and two-by-one pile groups. Model preparation, construction and instrumentation as well as modelling considerations are presented and discussed. The method for scanning and processing these model results is presented along with a simple application to a single pile.

1 INTRODUCTION

Scouring and flooding are identified as leading causes of bridge failure; of 503 reported cases of collapse between 1989 and 2000, 48% were a result of scour or flood (Deng, Wang, and Yu 2016). Even when collapse is not present, excessive settlement, tilt or movement can cause road closures and disruptions (Melville &Coleman 2011, Ettema, Nakato & Muste, 2006; Kayen et al., 2011). The fact that flood events and scour cause a disproportionate amount of bridge collapses does not necessarily indicate that floods are more prevalent than earthquakes or other hazards. Rather, it shows that floods and scour are much more likely to cause collapse when they occur, pointing to a fundamental weakness in design against such events.

Scouring is removal of foundation material, caused by flowing water. First studied by Shields (Shields 1936), in an open channel; scour occurs when the mean flow velocity (U) exceeds the critical flow velocity (U_c) (Pizarro, et al. 2020). The critical flow velocity is generally assumed to be primarily a function of the soil particle size, its weight (NOVAK and NALLURI 1974), the flow depth (h) (Richardson and Davis 1995) and the so called dimensionless sedimentological grain size (d^*) which takes into account the fluid properties (Hager and Oliveto 2002). Mean flow velocities in channel above the critical one ($U > U_c$) will promote the removal of soil and the overall lowering of the bed level of the channel, this is known as "general scour". If an obstruction, such as bridge foundation is placed within the channel, the local flow velocity can exceed the critical, and "local scour" can take place, even when the mean velocity remains below the critical limit ($U < U_c$). This is known as "clear water" scour and is the most common scenario for bridges in rivers (Figure 1). Both local and general scour can occur simultaneously. Of cases related to scour, around 60% are a result of local scour around the foundation (Lin et al. 2014). The maximum depth of this pattern occurs just in front of the object (foundation), and this depth (z) is used to characterise the severity of local scour. The scour depth (z) increases with time up to a fixed limit, which is termed the ultimate or equilibrium scour depth.

For circular piers of diameter D, the normalised scour depth (z/D) is related to the normalised flow intrusion (y/D), foundation size (D/d_{50}) and the normalised flow velocity (U/U_c). For other geometries, such as pile groups an equivalent diameter (D^*) is defined based on experimental results (Sheppard et al. 2004; Briaud, 2015b, 2015a).

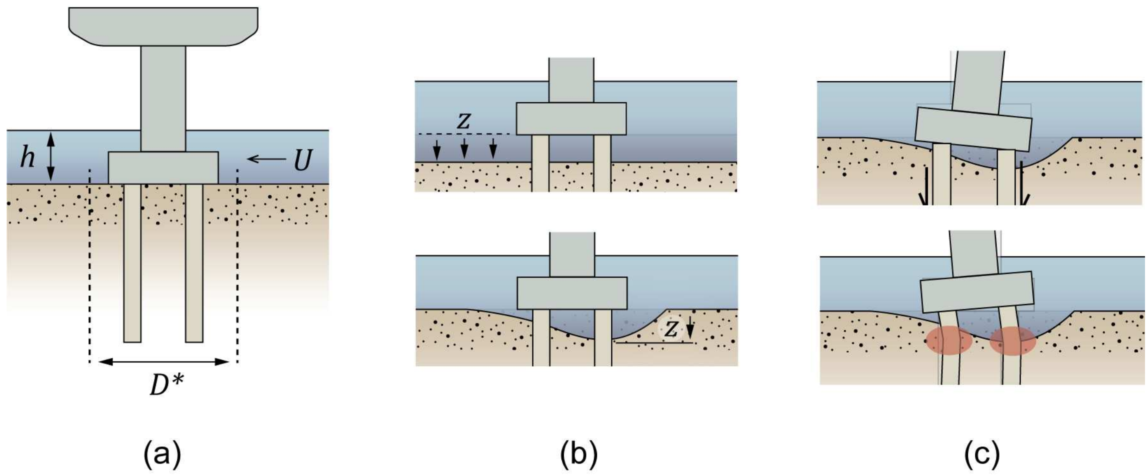


Figure 1 Scoured bridge pile systems with a) typical nomenclature b) general (Top) and local (Bottom) scour and c) typical failure modes for scoured piles.

Contemporary design methods propose the derivation of this scour depth based on a peak flow velocity for a design flood.

For designers, this ultimate normalised scour depth (z/D) is often the sole input parameter for foundation design. The most common design assumption is a total loss of foundation material to a depth equal to the equilibrium scour depth (z). Such a removal of soil poses significant challenges for a designer: in the case of piled foundations, this removes the confining soil close to the surface and can lead to excessive settlement or even buckling of the pile under the self-weight of the bridge deck (Lin et al. 2014). Particularly critical is lateral wind or earthquake loading: the exposed piles have to resist the entire moment load transmitted though the pier. The moment load is also increased because of the effective lengthening of the lever arm to the foundation reaction. This assumption has been shown to be unreasonably conservative in the case of caisson foundations (Ciancimino et al. 2021), its also fails to include any more complex 3D effects that could be crucial in the design of a foundation system.

Despite these apparent conservatisms in design, the prevalence of failures in the literature points to either an insufficient design methodology or greatly underestimated demand. This work aims to quantify the specific soil loss from a scoured foundation and its effect on piled foundation performance through the use of the "Hybrid" modelling technique. The hydraulic (scour) part of the phenomenon is modelled physically. The scoured geometry is then scanned and imported to a finite element package for further parametric study (L. Jones and Anastasopoulos 2023; Ciancimino et al. 2022).

2 PHYSICAL MODEL

Prototype structures are defined from a set of Swiss bridge foundation designs which include the most common 2x1 and 2x2 pile configurations as well as a single pile for comparison. The pile diameter is chosen as D = 1.2m, and the spacing set to 3D with a pile cap of thickness 1.6 D, all based on median values of the available foundation designs. The model scale is selected as 1:60, which produces reasonably sized models with pile diameters of 20mm. Pier diameters and shapes are similarly selected, with the 4 pile system having a larger pier. The model structures are 3D printed, with the cap made as a removable piece which allows for air pluviation of the soil material and scanning of the scoured foundation soil. The pile system is assumed to remain rigid, with no deformations of the pile or superstructure.

The model piles are glued to the base of a 400mm x 260mm model box, and sand is pluviated to a model depth of 50mm. The sand used is "Perth" sand, a fine sub-angular marine sand with d_{50} = 0.23mm. This is not intended to replicate a specific prototype, but provides a controllable, repeatable sand bed with which to conduct experiments. The sand is air pluviated to a relative density of 80-85%. The selection of soil material greatly impacts the scour process: specifically the rate of scour (for a given water flow) is controlled by the grain diameter, smaller grains will scour faster and with lower flow velocity. This scour rate is sensitive to the absolute grain size, leading to scaling issues especially when grains become very small. The ratio of the grain size to the pile diameter is also important, leading to relatively more scour (z/D) for ratios D/d_{50} < 100. Here that

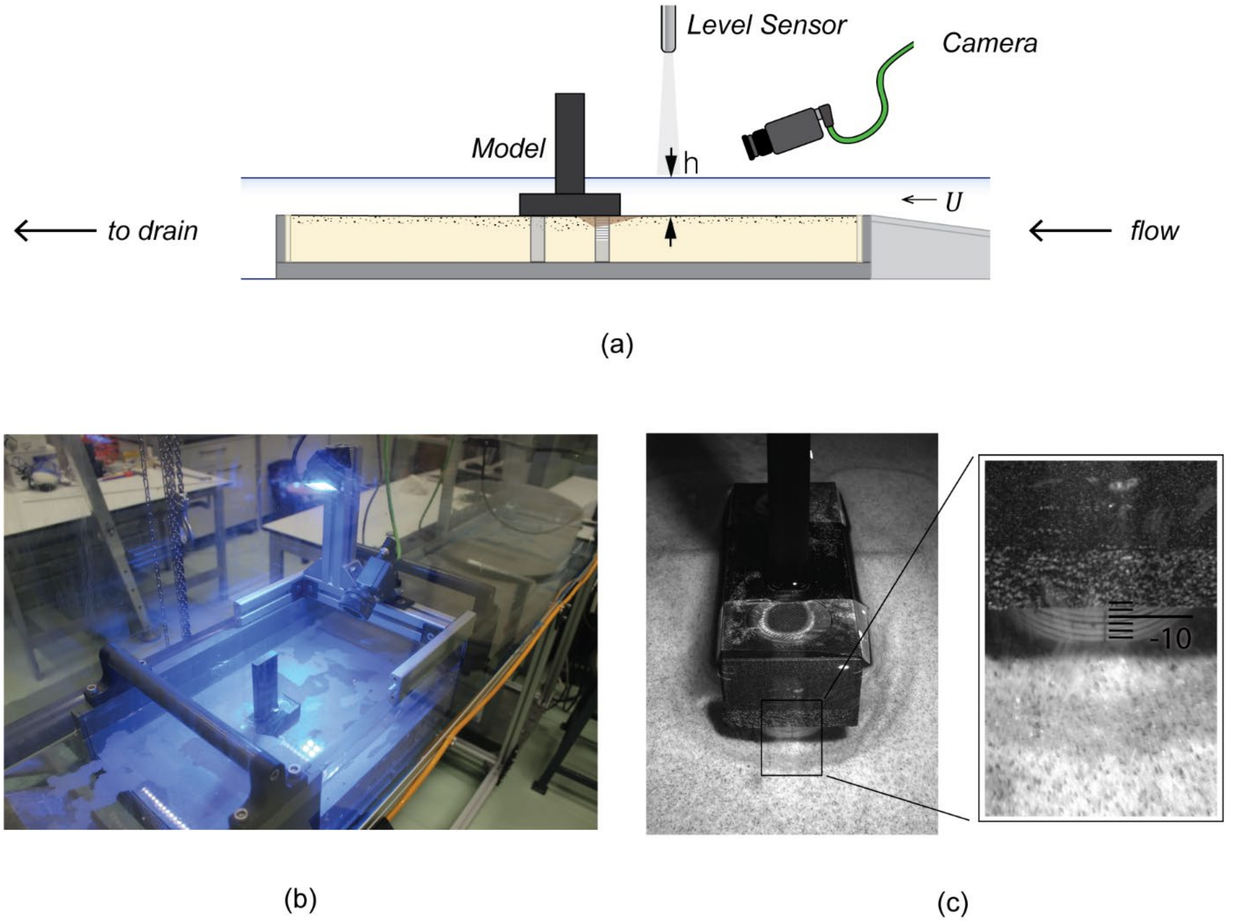


Figure 2 Schematic representation of Model Setup for 2 pile system b) experimental setup for 2-pile system, c) example image used to monitor scour depth progression.

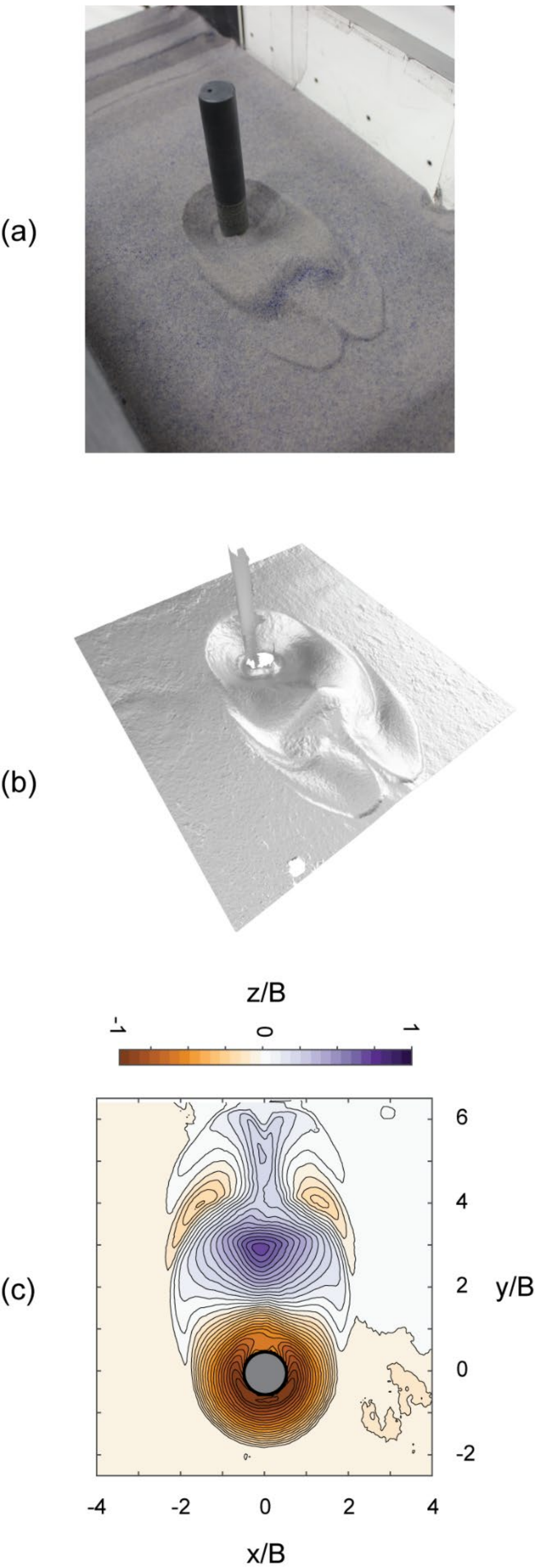
ratio is D/d_{50} = 87. If we assume that the soil grains are the same at model and prototype, we expect the prototype problem to have less ultimate scour depth. If the grains are scaled with the geometric length scale, this problem is not present.

The pile soil system is placed within the Miniaturised Tsunami Generator (MTG, Jones & Anastasopoulos, 2021)and subjected to a continuous flow having a depth of h =30mm and a flow ratio of U/U_{cr} = 0.6 (Figure 2). The level of the water surface close to the foundation is continuously monitored using an ultrasonic level sensor, and the flow velocity is estimated based on this measurement in conjunction with the volume flux (Q) of the pumping system.

The scour depth evolution is monitored though a camera above the foundation which looks through the water surface and is able to see the level markers printed onto the pile shaft (Figure 2c). Once the foundation has been sufficiently scoured, and the rate of scour has sufficiently slowed the experiment is stopped and the water drained from the flume. The pile cap is then removed and the scoured foundation pattern is 3D scanned.

3 SCANNING

For scanning, a *Shining3D EinScan Pro 2X* is employed. This scanner uses a combination of stereography and structured light mapping to rapidly produce high-accuracy scans. The device is hand-held and can be easily moved around the scoured model without disturbing the soil system. Reflective markers placed on the soil surface greatly aid in the scanning process and ensure that the soil surface and model structure can be well tracked during the scan. This is a major improvement over previous scanners employed at the institute, and can produce scanner surfaces with surficial accuracy on the order 0.1mm with excellent detail even in occluded or difficult positions. The scanner produces a raw mesh surface, in an STL (Stereolithography) format which can then be transferred to other programs for post processing (Figure 3). The mesh is transferred to the 3D modelling package *Rhino 7*. Any holes, small features or other imperfections can be removed in this step. The 2D surface is then converted to a 3D solid by adding



lateral and bottom faces. These faces will form the numerical boundaries in further steps. The pile is

Figure 3 Scoured physical model (a), raw 3D scan data (b) and processed scour surface (c) all for the same single-pile model.

separated into a separate object and the completed 3D solids are finally exported as ACIS (.sat) objects which can be read by various modelling software.

4 NUMERICAL MODELLING

Once the geometry has been established, the scour shape can be imported to the finite element ABAQUS CAE environment (SIMULIA 2021). The pile and soil are imported as separate parts. It was found that for most configurations, it is sufficient to model a “half-cut “ of the pile soil system, as the system is almost symmetrical about the centre of the pile (Figure 4). The soil is assigned numerical boundaries and the pile is inserted into the calculation domain. The detailed numerical model is not presented here, but it consists broadly of soil modelled using the Hardening-Softening Mohr-Coulomb (HSMC) material model (Agalianos and Anastasopoulos 2021)and pile modelled using the Concrete Damaged Plasticity model (CDP) with embedded rebar layers. The former HSMC model captures the monotonic behaviour of the model soil extremely well and is calibrated against a set of existing triaxial tests (L. Jones and Anastasopoulos 2023). The parameters of these models are available upon request to the authors. The choice of soil and model aims to ensure good compatibility between the scoured geometry and chosen soil. The CDP model is able to capture the behaviour of a circular concrete pile and ensures an accurate reproduction of system behaviour for different load-paths where failure in the soil or failure in the concrete pile may alternately be the dominant failure mode. The pile-soil interface is a strictly enforced “Hard” contact with a frictional surface behaviour with a friction angle of 25° . The top of the pile is connected to an eccentric point which represents the bridge deck through a rigid connector element. The bridge dead-load (V) as well as the mobilised horizontal force (H) or displacement (u) for pushover analysis are applied at this point.

The analysis is carried out in 3 steps: 1) Initial geostatic stresses are established under gravity. Geostatic equilibrium is found using the inbuilt iterative procedure of ABAQUS, the lateral earth pressures at rest (K_0) vary significantly around the scour feature, hence the need for such a procedure. Additionally: due to the process which creates the scour hole, the edges of the hole are on the very limit of stability, with slope angles approximately equal to the critical state friction angle. This means that the soil model used should well match the model soil: a different soil may not be statically stable with the

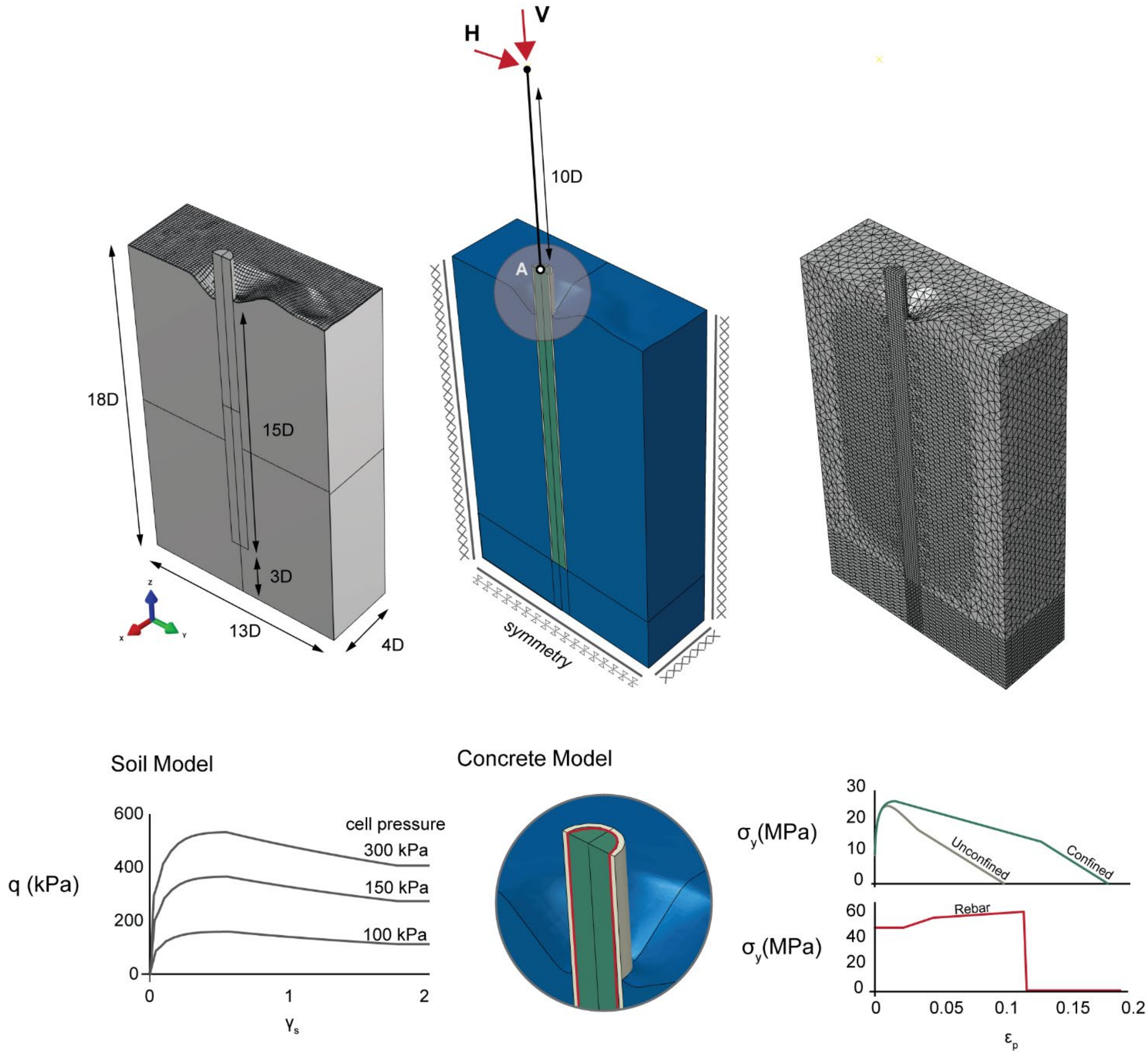


Figure 4 Overview of numerical model used for analysis including geometry, boundaries and material models.

chosen scour geometry. 2) An initial vertical factor of safety is established through a constant load at the level of the bridge deck. 3) A horizontal displacement (u) is applied at the bridge deck level to determine the pushover capacity.

5 RESULTS

Results are presented here briefly for the single-pile system as a proof of concept (Figure 5). For the single pile system, the presence of the scour hole has very little impact on the mobilised horizontal force at the bridge deck level. This is not unsurprising: the maximum scour depth is proportional to the total foundation width (D^*), which for the single pile system is equal to the pile diameter. The scour depth is therefore only a very small portion of the total foundation depth, and has little influence on the capacity. Further: for such a high moment-shear force ratios ($M/H = 10$), the failure is governed by structural failure (bending) within the pile. Here, it is possible to see that the formation of a plastic hinge occurs slightly lower down the pile for the scoured case, but the impact of this is very small. What can be observed however, is much larger stress concentrations within the soil for the scoured case. it is also clear that the response would be very different if the system were pushed in the upstream direction. Such a response is of interest for earthquake and wind loading. For systems where the ratio of total foundation width (D^*) to foundation depth (i.e. pile groups), based on some initial results, the effect of scour is much larger. However, this small example serves as a useful proof-of-concept and shows how such systems can be realistically modelled.

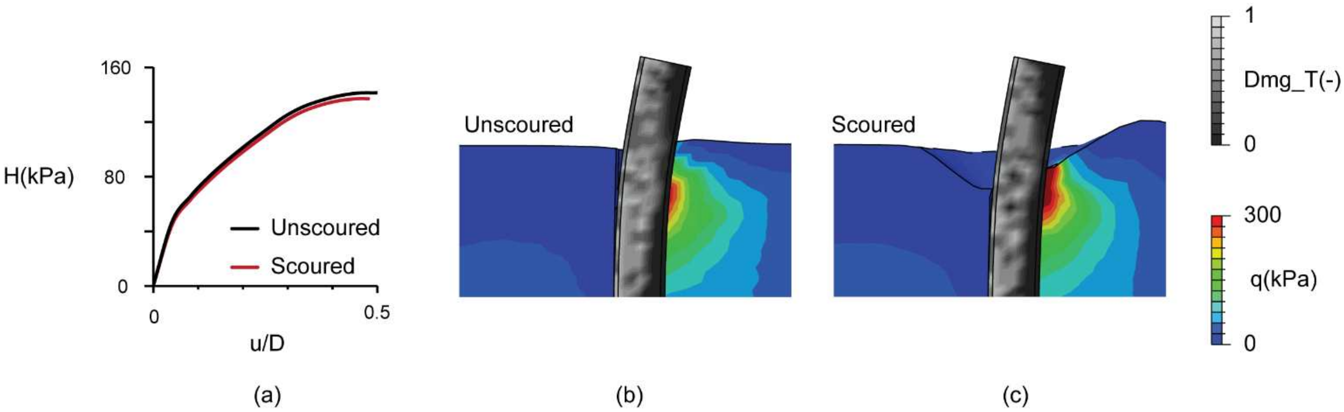


Figure 5 Results for the single pile configuration given in terms of (a) pushover force (H) vs displacement (u) as well as contours of stress and concrete tension damage for the unscoured(b) and scoured (c) cases.

6 CONCLUSIONS

Scour is a prevalent and severe problem for bridge foundations. Realistic and reproducible scour patterns can be produced at a small scale in the laboratory using the MTG device. The evolution of the maximum scour depth as well as the detailed scour pattern can be recovered from these experiments using 3D scanning and photography. This data can be used to create detailed numerical models which exactly reproduce the scoured system geometry. These models can then be parametrically investigated in order to highlight the effect of scouring on typical bridge foundations. For the simple single pile with large excentric load presented here, adoption of the traditional method of assuming a general scour down to the equilibrium local scour depth would be very conservative.

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