Effects of Geomorphological and Hydrological Changes on Piles Supporting Riverine Infrastructure

U. Ahmed[1] and D. E. L. Ong[1]
[1]*Research Centre for Sustainable Technologies, Swinburne University of Technology Sarawak Campus, Kuching, Sarawak, Malaysia*
E-mail: uahmed@swinburne.edu.my

ABSTRACT: In recent times, several cases of foundation failures associated to riverine structures such as jetties, bridges and wharfs have been reported. The geomorphological changes and hydrological changes of river bank slopes have been found to induce progressive soil movements before first time failure of the slope occurs. These cumulatively large movements can result in additional deflections and bending moments on the pile. The subsequent reduction in soil resistance due to the repeated soil movement patterns caused by these change has the potential to threaten the structural integrity of the pile. This paper presents a state of the art review of the recent developments in understanding soil-pile interaction for piles located in river bank slopes subject to soil movements induced by geomorphological and hydrological changes.

KEYWORDS: Passive piles, Soil movement, River bank slopes, Soil-pile interaction, Geomorphology, Hydrology

1 INTRODUCTION

The geology found commonly in the riverbanks of Sarawak consists of deep soft silty clay layers, which are underlain by rock bearing stratum. These riverbanks are sites to wharfs, ramps, jetties, bridge abutments and other riverine structures with foundations resting on or embedded in very soft clays. The riverbanks are subject to various man-made and natural forces including the effects of geomorphological and hydrological changes such as sedimentation, erosion/scouring and water level fluctuation which in turn affects the stability of the slope. The stability of the slope in turn is also influenced by the soil-pile interaction of the embedded piles.

The geomorphological and hydrological changes in the river bank slopes can result in soil creep movements and progressive failure. The movement brought about by these changes and repetitive fluctuation of the water level results in the formation of local shear zones within the slope. The shear zones propagate with continuing fluctuations before which first time failure of the slope occurs. If this soil movement before first time-failure is not considered during design, they can represent long term serviceability issues as this creep movement in the soil can result in large displacements of the soil and pile. This can also result in additional bending moments induced on the pile which can ultimately lead to failure of the foundation.

The design methods for slope stability currently used in practice are commonly based on limit equilibrium methods of analysis which can be used in everyday slope stability problems. This is not practical for complex problems involving progressive failure which occurs before first time failures and problems involving soil-pile interaction which require extensive calculation and analysis. The lack of commonly agreed design guidance for this problem is mainly due to the complexity of the problem as it involves consideration of non-linear stress strain behaviour of the soil, strain softening due to progressive deformations and pore water pressure changes variations within the soil over time. Even though research on slope stability issues has been on-going for the past few decades, detailed understanding on the effects of geomorphological and hydrological process on slope-pile systems is still needed. The analysis of these problems are also limited by the availability of data required, such as the soil movement and suction/pore water pressure changes at site. Computational power and capacity to carryout numerical analysis which can model the time dependent non-linear soil characterises and coupled hydro-mechanical analysis are available only in some geotechnical Finite Element Modelling (FEM) programs.

This paper presents an overview of the current state-of-the-art methods, practices and key areas of research into the effects of geomorphological and hydraulic changes on piles embedded on clayey river bank slopes. The first section reviews some of the relevant processes in relation to geomorphology and hydrological changes with emphasis on water level changes and fluctuations. Preceding sections provide some of the significant considerations and limitations in slope stability and soil-pile interaction analysis. A general review of the numerical and physical model studies in relation to modelling the problem have also been presented.

2 GEOMORPHOLOGICAL AND HYDROLOGICAL CHANGES

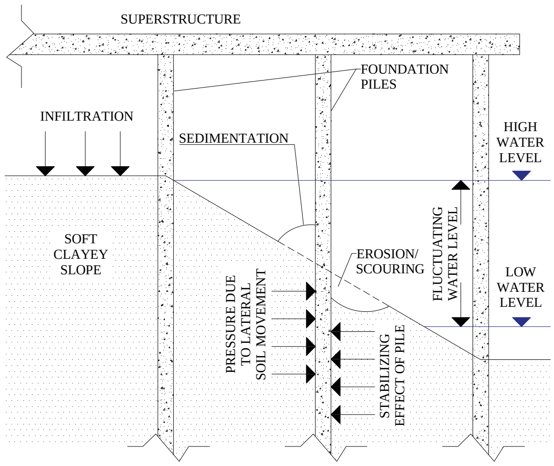

Figure 1 Key areas of research related to the effect of geomorphology changes on slope stability and soil-pile interaction

Bank material characteristics, bank geometry and characterises of flow events (peak river shape and shape of hydrograph) are important factors that need to be considered in analysing the stability of riverine slopes affected by geomorphological and hydrological changes (Dapporto et al., 2003; Rinaldi et al., 2004). Some of the geomorphological and hydrological processes involved include river morphology, sedimentation, erosion, scour, infiltration and rainfall, rising and lowering of water table and the seasonal fluctuation of the water levels (Figure 1). Some of these processes and the effect on supporting foundations are briefly discussed.

2.1 Sedimentation, Erosion and Scour

Sedimentation, erosion and scour processes could result in the reduction of slope stability due to fluvial entrainment or undercutting. They are also related to the river morphology and results in bank retreat and instabilities. In cohesive soils, bank erodability is related to the soil cohesion properties as well as bank flow characteristics (Rinaldi et al., 2008). The fluvial process related to sedimentation and scour near piles in banks have been studied in order to understand the process mechanisms and its effects on piles (Bayram and Larson, 2000; Sun and Wang, 2008; Ismael et al., 2015). Local scours form around piles due to the acceleration of flow near the piles which results in the formation of vortex systems. In areas where sediment flow is minimal, these scours could deepen due to the lack of sediment supply, resulting in reduced pile embedment and reduced bearing capacity of foundation (Li et al., 2013). Furthermore, erosion processes could also lead to instabilities and mass failure due to deformation of slope (Pizzuto, 2008; Papanicolaou et al., 2014). In recent years, the significance of scour and erosion at bridge abutment is being realized and efforts are being made to quantify flow measurements and local scours (Kw An and Melville, 1994; Melville, 2006; Ng et al., 2015).

On the other hand, when flow velocities are reduced, sediment mounds can also be observed. Thomas and Morin (2000) reported a study of a wharf built in soft silty clay experiencing movements due to soil sedimentation and movements induced by tidal fluctuations of 5.5 m. He reported gaps forming between access bridge and rear of the berths due to this movement. Investigation of the soil bed profile suggested that over 10 m of sedimentation occurred between years 1947 and 1998 due to the reduction in water velocity near pile structures. This resulted in soil movements at various depths and locations of piles, reaching up to a maximum of 30 mm in magnitude at some locations. Thomas and Margeson (2001) also carried out studies into the effects of sediment mounts on the stability of wharf structure in Port Klang. They observed that during low tides, the mound and slope tended to move seawards and reversed during high tides, while a cumulative displacement seaward remained. Furthermore, this cyclic movement induced on the sediment mounts reduced the shear strength due to remoulding of soil.

2.2 Infiltration

Infiltrations and moisture content variations in the soil after rainfall and storm events affect the pore water pressures and suction. Infiltrations into the soil may reduce the effective stresses while the total stresses and shear stresses are maintained (Picarelli et al., 2004). Depending on the permeability of the soil and the rate of infiltrations, the soil response to the change in pore water pressure can be delayed by several hours. This change requires either swelling or consolidation of the soil, which is controlled by the hydraulic properties of the soil. As such, variation of pore pressure and loss of matric suction after storm events could result in the deformation of slope and onset of first time failure. Furthermore, due to localized variations in the ground water levels and infiltration, the pore water pressure is continuously changing and susceptible to the changes in the weather.

Cases of slope failure after storm events have been reported, but are focused on the mass failure of slopes (Song et al., 2012; Ong et al., 2015). Rinaldi et al. (2004) presented the results of monitoring and modelling of pore water changes on a riverbank slope during flow events and found that a prolonged complex hydrograph with smaller peaks before a big peak is more unfavourable in terms of stability. Take and Bolton (2011) presented results of centrifuge studies carried out to understand the behaviour of slopes undergoing changes in the humidity and surface rainfall as represented by successive dry and wet seasons in real life. The authors studied the effects of seasonal moisture cycles and observed formation of plastics strains before the onset of failure due to regional soil softening. This phenomenon known as slope ratcheting was to be caused due to the dilatancy of frictional soil.

Lirer (2012) reported field trial test results from a three year monitoring program of a mudslide reactivation due to seasonal rainfall which triggered creep movement in the clay slope. Increased movements were observed over the three years which induced lateral pressures on the pile before it failed. A plastic hinge was observed to have formed in the piles just below the failure plane.

2.3 Fluctuating Water Levels

Typically three stages of water level needs to be considered in any analysis during flow events, where water levels are at the (a) maximum level, (b) minimum level and (c) fluctuating levels (Figure 2). The stress states during these stages are predominantly governed by the pore water pressures within the soils. During maximum and minimum water levels, if fixed conditions of geometry and water levels are maintained, the phreatic level line within the slope remains stable. Analyses of these slopes are relatively simpler and can be carried out by using limit equilibrium methods of analysis. According to Duncan (1996), soft soils with coefficient of permeability (hydraulic conductivity) less than 10^{-7} cm/s can be analysed as undrained soils. During drawdown and rising water levels, the external water level rapidly changes in relation to the change in the internal phreatic line (Jia et al., 2009). This is particularly significant when studying the geomorphology changes of a riverbank as the responses of the pore water pressure and soil movements could be out of phase with flow events, as highlighted by Rinaldi et al. (2004).

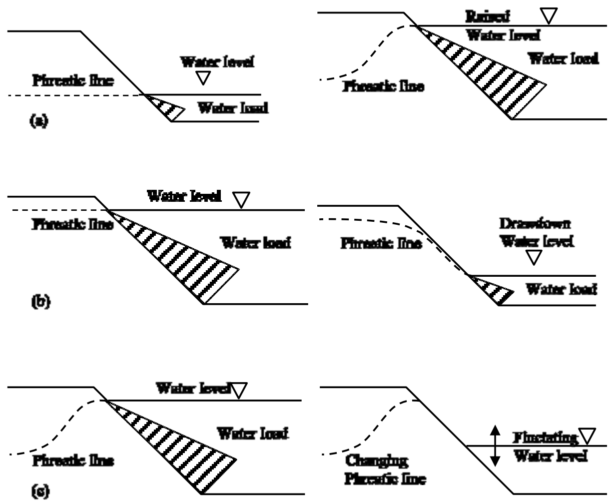

Figure 2 Stages of water level changes (a) drawdown water level (b) raised water level (c) fluctuating water level

Various studies have been carried out to understand the behaviour of soil during rapid drawdown (Moregenstern, 1963; López-Acosta et al., 2010; Fredlund et al., 2011). The hydrostatic pore water conditions change during drawdown water levels, when the total stresses are changed at different rates relative to the changes in the external water level. This could result in areas with excess non hydrostatic pore water pressures and reduced shear strengths due to progressive movements (Wang et al., 2012). Existing slip lines within the slope can also reduce the safety of the slope.

The deformation of the soil slope is governed by the soil characteristics as well as soil loading history and an overall reduction of the slope equilibrium might be observed if these parameters change. Depending on the strains induced by the deformations, the soil can exhibit elastic or plastic behaviour. Large strains lead to the formation of plastic shear zones within soil where the full shear strength of the soil is mobilized. These plastic zones which can propagate along the slope, results in the lateral movement of the soil (Duan and Wang, 2008).

In a study carried out by Zhan et al. (2006) to investigate the effects of reservoir level changes on the bank stability, it was found that the minimum factor of safety occurs during reservoir drawdown conditions. The negative pore pressure (suction) contribution together with the frictional resistance of the soil and the thrust force of reservoir water were the main factors determining the factor of safety. Reduced shear strengths due to creep mechanisms and loss of the external water loads resulted in large deformations. The critical duration with lowest factor of safety was found to have occurred when the draw down level reached 1/3 slope height.

During the reversal of drawdown process where the water level is rising, stabilizing external water load is applied on the slope. However, rising water levels may also lead to local instabilities due to stress redistribution, loss of negative pore pressures and seepage effects. The change in the external water loads, flow condition and pore water pressure has been found to reduce the stability and factor of safety of some slopes (Cojean and Caï, 2011; Johansson and Edeskar, 2014). In a study conducted by Jia et al. (2009) on a large scale reservoir model, when water levels were increased initially, vertical settlements were observed at the crest of the slope due to wetting induced soil collapse. A slope of 1:1 (H:V) was prepared in sandy silty soil and the water level was increased at 2 m steps every 12-hour interval. The increased water levels also decreased the shear strength of the soil due to the loss of initial matric suction, which was measured highest at the crest of the slope. This resulted in the inclination of the slope being reduced from 45 to 33 degrees. The vertical stresses in the slope also increased to a peak during the water level rise followed by a gradual decrease thereafter (Figure 3). Changes seen in the horizontal stresses with water level rise were attributed to the entrapped air surrounding the measurement instruments.

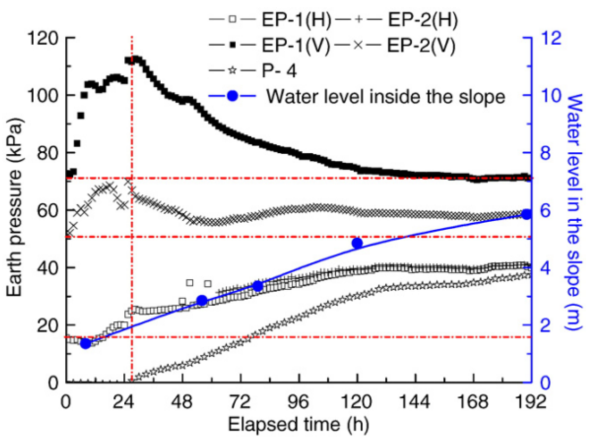

Figure 3 Measured results from vertical (V) and horizontal (H) earth pressure cells (Jia et al., 2009)

Studies have been carried out to study the effect of fluctuating water levels on bank slope stability (Yan et al., 2010; Jye et al., 2014). Sullivan (1972) reported the study of a wharf subject to tidal fluctuations resulting maximum water levels at 4.9 m above normal levels during the period from July to October. Low water levels were observed at 1.5 m below normal levels during the winter months. The author reported tidal fluctuation induced wharf movements of 25 mm. Casagli et al. (1999) also presented the results of an instrumentation program carried out to investigate the role of pore water pressure in slope stability. The seasonal variation of the slope stability was studied based on the data obtained from the instrumentation program. They noted that during low flow periods, the matric suction contributed to the shear strength allows the slope to maintain stability at steep angles. During rainfall and flow events, this suction disappears, reducing the factor of safety of the slope and triggering mass failure (Figure 4).

Studies on landslide stability based on the hydraulic properties of soil and fluctuation velocity of reservoir water level has also been carried out by Li and Feng (2008); Song et al. (2015). They reported the maximal accumulated deformation of two slide failures which reached 1428 mm and 451 mm in two water fluctuation cycles. Parametric studies of different slope angles and pile spacing were studied. The authors developed Soil-Water Characteristic Curves (SWCC) to be used in the analysis of the studied reservoir landslide and further analysis was carried out on SEEP/W software. Fitting parameters based on equation by Fredlund Xing (1994) were used to develop the SWCC.

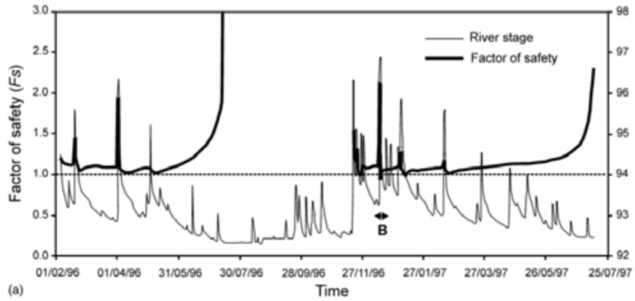

Figure 4 Variation of factor of safety with seasonal variation of water levels

3 STABILITY OF SLOPES

Slope movements can be categorized as at pre-failure, first time failures and post failure with occasional reactivation of slides thereafter (Leroueil and Picarelli, 2012). In the initial stage before a first time failure occurs, the soil slope undergoes progressive failure induced by geomorphological and hydrological changes (Figure 5). Urciuoli et al. (2007) studied the post failure strengths and behaviour of sand and clay slopes. He determined that progressive failure occurs if there is (1) brittle soil, (2) non uniformities in the distribution of shear stresses, (3) local shear stresses at peak strength of the soil; or (4) boundary conditions that induce strains. Since naturally formed slopes have most of these conditions, progressive failure is common and can occur during the pre-failure movement periods (Hungr et al., 2014).

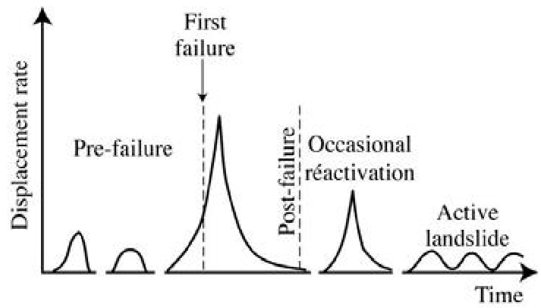

Figure 5 Stages of slope movement (after Leroueil and Picarelli (2012)

Various methods of slope stability analyses based on limit equilibrium have been developed. The simplified Bishop (1955) method is proven to give fairly accurate results for very long and shallow planar slip surfaces. For slip surfaces of arbitrary shapes, generalized methods of slices such as Janbu's generalised procedure (1973), Spencer's procedure, Morgensten-Price (1965) method or Spencer (1967) method may be used. These methods have been compared and given that all the equilibrium conditions are satisfied, the variations of the results from each method ranged at 5% (Fredlund and Krahn, 1977; Duncan and Wright, 1980; Fredlund et al., 1981).

Even though these methods provide a practical and conservative means of design, factors such as non-linearity of soil stress-strain relationships due to local zones of fully plastic behaviour under working load and softening behaviour due to creep movement needs to be considered (Jeong et al., 2003). In brittle material, local failure zones may propagate at small displacements, leading to instability or progressive failure. Inconsistencies in using linear elastic models in carrying out analysis related to excavation related problems and problems related to the use of bilinear stress strain relationships in analysing failure of stiff clays has shown that the use of such models are not sufficient to provide an accurate picture of the behaviour of soils (Jardine et al., 1986). The strain softening behaviours of the soil has also been reported to be significant in the analysis of highly plastic clay slope stability (Duncan, 2013). This behaviour cannot be modelled in the limit equilibrium analysis which assumes slope failure occurs along the slip surface at the same time.

4 SOIL PILE INTERACTION

Based on the load transfer mechanism, piles could be generalized as active or passive piles. In active piles, loads are directly applied to the pile and transferred to the soil while in passive piles, the load is applied by the soil and is influenced by the presence of pile. In case of river bank structures, these two scenarios are applicable where piles are subject to wave, wind, impact and other external loads as well as passive loads due to lateral soil movement. While the design guidance for active piles is fairly well established, it is often difficult to analyse piles under lateral loading induced by soil movement.

In designing pile foundations, designers are required to satisfy both strength and serviceability limit state conditions. In riverine slopes undergoing soil movements, the piles may not be designed for lateral soil movements induced by the geomorphological and hydrological changes. This can lead to two conditions: (1) the ultimate bending moment developed exceeding the lateral pile capacity and resulting in formation of cracks in the pile or (2) the displacement of the pile exceeding the serviceability limit state and resulting in differential movements and distortion of superstructure.

The analysis of laterally loaded piles can be described as computing the pile deflection and bending moment as a function of depth below the surface and can be analysed based on semi-empirical or theoretical analysis (Stewart et al., 1993). Semi empirical analysis provides practical means of analysis. They can be carried out by displacement / pressure based methods (Chen and Martin, 2002; Galli and di Prisco, 2013; Guo, 2013) and requires inputs such as free field soil movement and limiting soil pressures. Methods based on the theory of subgrade reaction can be used by assuming a varying subgrade modulus with depth and the soil modelled in linear elastic conditions (Meyer and Reese, 1979).

Chow and Yong (1996) presented a theoretical method using the idealized subgrade reaction and applied the method developed by Poulos (1973) to a non-homogenous solution. The lateral soil stiffness (K_h) and limiting soil pressure (P_y) was used as the main parameters. The method was developed to be used by inputting the soil lateral movements measured from onsite inclinometer data. Chen and Poulos (1997) also developed a theoretical procedure to analyse lateral soil movement on vertical piles embedded on horizontal ground and slopes. By inputting the diameter, stiffness and length together with the soil Poisson's ration, Young's Modulus and limiting soil pressures, they analysed several cases and a model test to verify the method. A boundary element program "PALLAS" was used to analyse the single pile and pile group cases. This required the limiting soil pressures to be estimated beforehand based on information relating to piles under lateral loading. Furthermore, the group effects needed to be pre-defined by using finite element analysis. The authors also provided design charts in case where information is unavailable, but noted that the results are more accurate for ratio of soil movements to pile diameters less than 10%. Goh et al. (1997) also proposed a simplified numerical approach derived from analysis of FEM in which non homogeneous soil strength, pile stiffness and pile head fixity can be considered. The lateral soil movement induced due to embankment loading is determined from FEM data or measured data. This data is subsequently used as input to analyse the pile response to the movement. The lateral stiffness of the soil was derived from a modification of Broms (1964) formula.

Ong et al. (2015) carried out numerical and finite element analysis to determine the limiting soil pressures and its effect on a pile group. The numerical method by Chow and Yong (1996) was used with the free-field movements measured from site and defined limiting pressures. Subsequent 2D FE modelling carried by the authors used smearing techniques where the pile properties are applied to an equivalent wall in the plane strain analysis to achieve accurate results with this numerical method.

4.1 Pile effect on slope

Pile properties such as pile stiffness, diameter, pile head condition and adhesion can affect the lateral capacity of the pile and the stability of the slope. Won et al. (2005) noted that where piles with large stiffness (E_p= 25 GPa) are installed, the stability of the slope is less sensitive to the pile head conditions. Short piles of high stiffness or free headed/floating bases have been reported to result 10 times the maximum bending moment for fixed head piles (Guo and Lee, 2001; Sawant and Shukla, 2012). Furthermore, pile adhesion and diameter can affect the ultimate soil resistance and modulus of subgrade reaction in the soil (Georgiadis and Georgiadis, 2010; Kim and Jeong, 2011).

The stabilizing effect of pile on slopes have been studied for clay and sand slopes (Chen and Martin, 2002; Kourkoulis et al., 2011; Guo, 2013) but limited studies have been carried out in riverbank slopes. Hong and Lee (2009) reported a study where lateral movement of piled bridge abutments on natural soft soil slopes undergoing lateral soil movements was analysed. While analysing the data from forty-three abutments, the authors also investigated the stabilizing effect of the piles on slope. They reported that the lateral movement on bridge abutment occurs when the slope factor of safety is below 1.5 and suggested a higher factor of safety for slopes with stabilizing piles.

4.2 Geometry of slope

Geometry of slope such as inclination of slope and location of the pile along the slope also affect the lateral pressure induced on the pile. Georgiadis and Georgiadis (2010) reported that increasing the slope inclination can increase the deflection and bending moments of the embedded piles. The bending moments were reported to be more sensitive to the soil inclination than the pile adhesion factors. Georgiadis et al. (2013a) also found a 20 and 40 percent reduction in bearing capacity for smooth piles near 1:2 and 1:1 slopes respectively, compared to the lateral bearing capacity for piles on horizontal ground.

Won et al. (2005) carried out a series of stability analyses of pile-slope systems in order to understand the coupled response of the pile and the slope stability. An uncoupled analysis of the slope was initially carried out and compared with the results of the coupled pile-slope system. Shear strength reduction technique was used to determine the reduction factor required for piles at different locations along the slope and with different pile spacing. Authors reported that the critical slip surface changed with the installation of piles which is consistent with other literature. They noted that the maximum pressure acts on the piles in mid-slope. This agrees with Gao et al. (2015) who reported that the most effective location to install stabilizing piles to be between crest and mid-slope locations.

4.3 Group pile effects

Studies have also been carried out to investigate the group pile effects embedded on slopes underdoing lateral pressure. Pan et al. (2002) also studied the lateral resistance of pile groups in coupled and uncoupled conditions. He reported that the group factor decreases with pile spacing and also reported group affects being observed even with pile spacing at 5D. Qin and Guo (2012) reported that for group piles oriented in a row, no significant difference in bending moments were observed for uncapped or capped pile groups. Georgiadis et al. (2013b) reported that the reduction factor for the lateral resistance of group piles varies with depth and is not linear as is conventionally assumed.

4.4 Soil limiting pressures

Lateral response of a pile embedded in soil undergoing lateral movements is found to be governed by the limiting soil pressure (P_y) and is defined as the point at which soil flows past the pile. Determining this limiting pressure of soil has been focus of many researchers. Different authors have suggested different values to be used as this limiting pressure (Table 1) as the impact of limiting pressure varies from case to case (Chen, 1994).

In the study by Chow and Yong (1996) the lateral soil stiffness was estimated from the Soil Young's Modulus while the limiting pressure was assumed to vary linearly from 3 C_u at ground surface to 9 C_u at depth of about 3.5 diameters to account for the near surface affects (where C_u is the undrained shear strength of the soil at the particular depth). Goh et al. (1997) used a ultimate limiting soil pressure of 10.5 C_u while Pan et al. (2002) found that the ultimate pressure range from 7.1 C_u to 8.5 C_u when piles are arranged in a row. Bauer et al. (2014) proposed the maximum normalized lateral pressure (Py/Cu) which lies on a range of 3.5 to 8. Ong et al. (2015) reported that the ratio of normalized limiting pressure and undrained shear strength needs to be limited to 9 if post excavation shear strengths are used in the analysis.

Table 1 Proposed limiting pressure values by different authors (updated from Bauer et al. (2014)

Reference	Derivation	P_u
Chen (1994)	FE-Analysis	$11.75 \cdot C_u \cdot d_p$
Bransby (1995)	FE-Analysis	$10.6 \cdot C_u \cdot a_p$
Chow and Yong (1996)	FE-Analysis	$3 - 9 \cdot C_u$
Goh et al. (1997)	FE-Analysis	$10.5 \cdot C_u$
Pan et al. (2002)	1 g model tests	$8.33 \cdot C_u \cdot a_p$
Bauer et al. (2014)	FE-Analysis	$3.5 - 8 \cdot C_u$
Ong et al. (2015)	FE-Analysis	$6 \cdot C_u$

Where P_y = lateral pressure on the pile; C_u = undrained strength; d_p = pile diameter; a_p = edge of the pile.

These studies use values of ultimate soil pressure within the range of 9-12 C_u as is commonly adopted for both excavations and embankment loading induced movements. While these two condition represent different loading patterns (loading and unloading), reviewing the effects of geomorphological and hydrological effects on piles embedded in clayey riverbank slopes suggests a quasi-cyclic nature of passive loading/unloading. The soil movements and the loading on piles during high and low water levels tends to change while the deflection of the pile cumulates (Figure 6). Studies on the effect of limiting pressures on pile integrity for such repetitive loading conditions leading to failure have not been found.

5 NUMERICAL AND PHYSICAL MODELLING

2D and 3D finite element – finite difference methods are useful tools in mass failure analysis and can accommodate such considerations as soil non linearity and softening behaviours accurately. Finite Element models of the soil pile response is typically modelled in Plane-Strain, Axisymmetric or Three Dimensional Analysis (Stewart et al., 1993). Analysis using elastic-plastic models allows local yielding but needs to allow non-linear elasticity before yield and strain softening behaviour to model the creep deformation characteristics. FEM results have been reported to give a realistic result of the bending moment as steady state and external pore water pressures can be calculated based on the phreatic levels (Zhou et al., 2014).

Duncan (1996) presented a state of the art paper on the use and accuracy of limit equilibrium and finite element modelling techniques to achieve realistic results in slope stability analysis. The author carried out a series of tests using different types of stress strain relationships for comparison using data from a range of dams, slopes, fills and embankments. In FE models using free field soil movement and pore pressure, challenges such as soil non linearity, inhomogeneity, time dependency and other interactions can be accounted in the model (Kelesoglu and Cinicioglu, 2010).

The process of fluctuating water levels involves changing ground water conditions. Even though the behaviour of the slope during rising and drawdown water levels can be considered separately, the repetitive variations in the water level needs to be modelled to represent the deformation characteristics and flow conditions with time dependent boundaries (Johansson and Edeskar, 2014). This is possible by carrying out a coupled or uncoupled hydro-mechanical numerical analysis. Coupled analysis has been reported to give a more accurate and realistic result than uncoupled analysis of slope stability and soil pile interactions, where water level fluctuation plays a significant role (Jeong et al., 2003; Won et al., 2005; Wang and Zhang, 2013). The limitations of using uncoupled transient seepage analysis have been extensively discussed by VandenBerge et al. (2015).

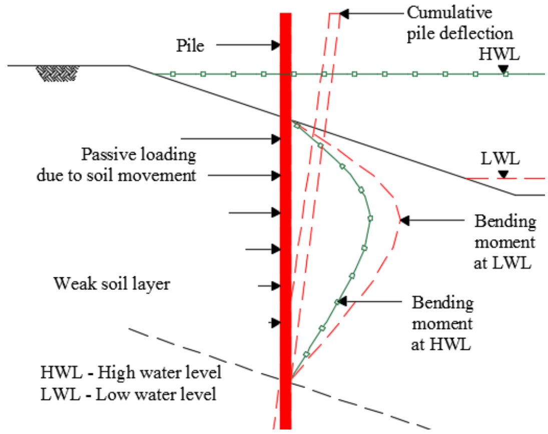

Figure 6 Schematic of pile deflection and bending moment induced due to progressive soil movement

The erodability of bank also needs to be considered and can be analysed using excess shear stress formulae. Near bank-shear stress and erodability parameters are difficult to characterize, particularly due to its temporal variation brought about by the changes in the water content (Rinaldi and Nardi, 2013). Advances in modelling the geomorphological and hydrological changes have been reviewed by Rinaldi and Darby (2007); Rinaldi et al. (2008). One major research gap highlighted by the authors are the lack of models which combines both the hydrological and stability models.

Finite element programs such as PLAXIS 3D and SEEP/W can be used to carry out coupled time dependent analysis based on non-linear constitutive models. In the study carried out by Zhan et al. (2006) the authors analysed the factor of safety based on a limit equilibrium method in SEEP/W software. The contribution of negative pore pressures to shear strength was considered by using Fedlund's shear strength equation for unsaturated soils. This effect of negative pore water pressure / suction on the bank deformation is an important modelling consideration (Rinaldi and Nardi, 2013). Recent developments in hydraulic models such as Soil Water Characteristic Curves serves to relate the soil suction with the saturation and can be used to determine the soil parameters required for the modelling via a curve fitting process (Leong and Rahardjo, 1997; Galavi, 2010). Limitations in defining the initial SWCC required to define the suction parameters has been a major challenge in coupled hydro mechanical analysis.

Coupled hydro-mechanical analysis could prove to be of significance when considering the combined effects of the slope stability; geomorphology and hydrology changes; and the soil-pile interaction. While the upper zones of the slope might be undergoing cyclic-near surface movements due to water level fluctuation, progressive failure of the slope occurs on a larger time scale. Furthermore, considering the effect of geomorphology changes related to erosion, scour, sedimentation and rainfall infiltration on slope stability and soil pile response could prove to be additionally helpful in understanding the long term stability of the slope and riverine structures.

5.1 Physical models

Centrifuge technology and 1g model tests have been useful tools in the analysis of slope stability and soil pile interaction problems. The useful applications of centrifuge modelling in understanding soil-pile interaction situations where lateral soil movements occur has been discussed by Leung (2006). Wang and Zhang (2013) carried out a series of centrifuge tests to study the effect progressive failure in a pile-slope system with soft clay. Lateral soil movements were induced by surcharge plates. Ultimate pressure on piles increased when the pile was moved to mid-slope instead of the toe and by increasing the pile tensile strength. Progressive failure was observed with increasing vertical loads before cracks appeared near the loading plates. The authors defined this as the start of the failure stage. Secondary slip surfaces were also observed when the pile was located nearer to the toe of the slope (Figure 7).

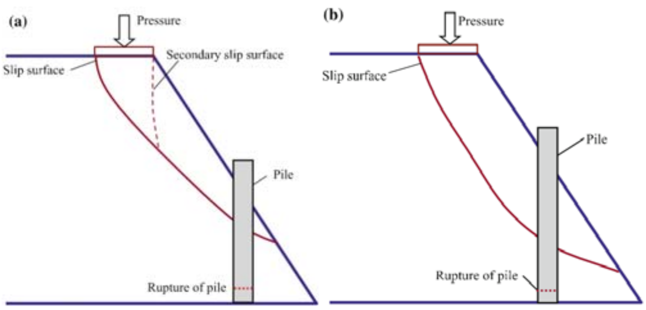

Figure 7 Failure configuration of slope and piles for piles located at (a) toe, (b) mid-slope (after Wang and Zhang (2013))

Shaojun et al. (2015) carried out centrifuge model tests at 100g for sandy clay slope stability of a reservoir by varying the water levels (Figure 8). Two conditions were studied where the first series of tests were carried out with the water level fluctuated between 2.5 m for the first few cycles and then varied between 4 m in the subsequent cycles. In the second condition, the water levels were varied between 6.5 m for the first few cycles and then varied between 8.5 m. The authors concluded that the highest slope movement, which propagates from the toe of the slope, occurs during the first cycle of water level fluctuation. The variation of magnitude of water level changes also resulted in higher movement.

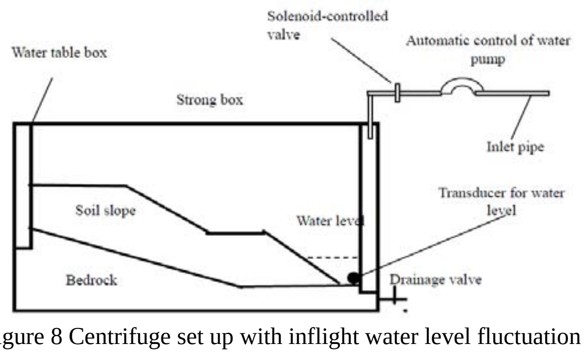

Figure 8 Centrifuge set up with inflight water level fluctuation system (after Shaojun et al. (2015)

According to the physical model studies presented, the soil movement during the first few cycles of water level fluctuation tends to be significant. When modelling the water level fluctuation in river bank which has undergone unknown number of cycles of fluctuation, this initial movement needs to be considered since they would not represent the initial conditions in an actual riverbank slope. As soil loading history is a significant parameter governing its behaviour, the changes in soil shear strength due to the repetitive deformations need to be considered.

6 RESEARCH GAPS AND CONCLUDING REMARKS

A summary of the literature found on the soil structure interaction of piles embedded on soft clay slopes subject to geomorphological changes and hydrological changes has been presented. Based on the studies reviewed, the following conclusions can be drawn:

1. Geomorphological and hydrological changes such as seasonal variations in river water level and flow rates, sedimentation, erosion and changes in the bank geometry can negatively influence the stability of existing slopes and pile foundations. Scouring and erosion leads to reduced bearing capacity of pile foundation while sedimentation can result in additional loads on piles due to formation of sediment mounds which are susceptible to the influences of water level fluctuation. Furthermore, the overall deformation of the slope leads to higher slope inclination and reduced factor of safety of slope.
2. Fluctuating water level and changes in moisture contents due to infiltration have been found to induce soil movements, which in turn results in additional bending moments and deflection of piles. The continuous and seasonal changes in the pore water pressure and suction results in progressive movement of soil. It has been found that while the minimum factor of safety occurs during drawdown, rising water levels could also lead to local instabilities due to stress redistribution, loss of negative pore pressures and seepage effects.
3. Progressive failure before first time failures is a common occurrence in natural slopes due to the said changes in pore water pressure within the slope. Factors such as non-linearity of soil stress-strain relationships due to local zones of fully plastic behaviour under working load and softening behaviour due to creep movement needs to be considered when analysing such slopes. Limit equilibrium analysis which assumes slope failure occurs along the slip surface at the same time cannot be used to predict such movement.
4. Several methods of predicting the pile response to lateral soil pressures have been presented by different author including empirical, pressure-displacement and finite element methods. Semi empirical analysis methods provide a practical way of predicting soil-pile response. This needs to be further investigate for use in riverine foundation analysis as these solutions commonly require soil movements, lateral stiffness of soil and limiting soil pressures as main input. Some of the factors which influences the pile-slope systems have also been briefly discussed including the effects of pile properties, geometry of slope and group pile effects.
5. The soil limiting pressure depends on the loading conditions. Commonly adopted values of 9-12 C_u need to be reconsidered for river bank slopes where soil movement is quasi-cyclic in nature and undergoes repetitive loading and unloading. Studies of limiting pressure for such loading condition have not been found in literature.
6. Developments in coupled soil-pile interaction and coupled hydro-mechanical slope stability analysis could prove to be useful tools in analysing the long term serviceability problems of riverine structures. Accurately modelling the soil-pile interaction requires coupled hydro-mechanical analysis where the fluctuation in the pore water pressures are modelled. Constitutive models are used to describe the soil stress strain relationships while Soil Water Characterizations curves are

used to describe the soil suction/saturation relationships. Studies found in literature have been either limited to studies of slope stability where water fluctuation is considered or to studies of uncoupled soil-pile interaction analysis.

7. According to the physical model studies reviewed, the largest slope deformation due to water level fluctuation occur during the first cycle of drawdown. This needs to be considered when carrying out physical model tests on riverbank slope as in the real case, river bank slopes would have undergone unknown number of fluctuations.

7 REFERENCES

Bauer, J., Kempfert, H. and Reul, O. (2014) Lateral pressure on piles due to horizontal soil movement — 1 g model tests on single piles and pile rows, Physical Modelling in Geotechnics, pp 839-845.

Bayram, A. and Larson, M. (2000) Analysis of Scour around a Group of Vertical Piles in the Field, Journal of Waterway, Port, Coastal and Ocean Engineering, 126, no. 4, pp 215-220.

Bishop, A. W. (1955) The use of the Slip Circle in the Stability Analysis of Slopes, Géotechnique, 5, no. 1, pp 7-17.

Bransby, M. F. (1995) Piled foundations adjacent to surcharge loads, University of Cambridge.

Broms, B. B. (1964) Lateral resistance of piles in cohesive soils, Journal of the Soil Mechanics and Foundations Division, 90, pp 27-64.

Casagli, N., Rinaldi, M., Gargini, A. and Curini, A. (1999) Pore water pressure and streambank stability: results from a monitoring site on the Sieve River, Italy, Earth Surface Processes and Landforms, 24, no. 12, pp 1095-1114.

Chen, C. Y. and Martin, G. R. (2002) Soil–structure interaction for landslide stabilizing piles, Computers and Geotechnics, 29, no. 5, pp 363-386.

Chen, L. T. (1994) The effect of lateral soil movements on pile foundation.- "Effect of Lateral Soil Movements on Pile Foundations".

Chen, L. T. and Poulos, H. G. (1997) Piles Subjected to Lateral Soil Movements, Journal of Geotechnical and Geoenvironmental Engineering., 123, pp 802.

Chow, Y. K. and Yong, K. Y. (1996) Analysis of Piles Subject to Lateral Soil Movements, Journal of the institute of engineers, Singapore, 36, pp 43-49.

Cojean, R. and Caï, Y. J. (2011) Analysis and modeling of slope stability in the Three-Gorges Dam reservoir (China) — The case of Huangtupo landslide, Journal of Mountain Science, 8, no. 2, pp 166-175.

Dapporto, S., Rinaldi, M., Casagli, N. and Vannocci, P. (2003) Mechanisms of riverbank failure along the Arno River, Central Italy, Earth Surface Processes and Landforms, 28, no. 12, pp 1303-1323.

Duan, Q. W. and Wang, Y. J. (2008). Study on deformation parameter reduction technique for the strength reduction finite element method "Proceedings of the 10th International Symposium on Landslides and Engineered Slopes", 2008 Xi'an, China. pp 663-669.

Duncan, J. M. (1996) State of the Art: Limit Equilibrium and Finite-Element Analysis of Slopes, Journal of Geotechnical Engineering, 122, no. 7, pp 577-596.

Duncan, J. M. (2013). Slope Stability Then and Now "Proceedings of the 2013 Geo-Congress: Stability and Performance of Slopes and Embankments III", 2013. 2191-2210.

Duncan, J. M. and Wright, S. G. (1980) The accuracy of equilibrium methods of slope stability analysis, Engineering Geology, 16, no. 1-2, pp 5-17.

Fredlund Xing, A., D (1994) Equations for the soil-water characteristic curve, Canadian Geotechnical Journal, 31, pp 521-532.

Fredlund, D. and Krahn, J. (1977) Comparison of slope stability methods of analysis, Canadian Geotechnical Journal, 14, no. 3, pp 429-439.

Fredlund, D. G., Krahn, J. and Pufhal, D. E. (1981). The relationship between limit equilibrium slope stability methods "Proceedings of the International Conference on Soil Mechanics and Foundation Engineering (Vol 3)", 1981. 409-416.

Fredlund, M., Lu, H. and Feng, T. (2011) Combined Seepage and Slope Stability Analysis of Rapid Drawdown Scenarios for Levee Design, Geo-Frontiers 2011, pp 1595-1604.

Galavi, V. (2010) Internal Report Plaxis. Groundwater flow, fully coupled flow deformation and undrained analyses in PLAXIS 2D and 3D, pp 1-290.

Galli, A. and di Prisco, C. (2013) Displacement-based design procedure for slope-stabilizing piles, Canadian Geotechnical Journal, 50, no. 1, pp 41-53.

Gao, Y.-f., Ye, M. and Zhang, F. (2015) Three-dimensional analysis of slopes reinforced with piles, Journal of Central South University, 22, no. 6, pp 2322-2327.

Georgiadis, K. and Georgiadis, M. (2010) Undrained Lateral Pile Response in Sloping Ground, Journal of Geotechnical and Geoenvironmental Engineering, 136, no. 11, pp 1489-1500.

Georgiadis, K., Georgiadis, M. and Anagnostopoulos, C. (2013a) Lateral bearing capacity of rigid piles near clay slopes, Soils and Foundations, 53, no. 1, pp 144-154.

Georgiadis, K., Sloan, S. W. and Lyamin, A. V. (2013b) Undrained limiting lateral soil pressure on a row of piles, Computers and Geotechnics, 54, pp 175-184.

Goh, A. T. C., Teh, C. I. and Wong, K. S. (1997) Analysis of piles subjected to embankment induced lateral soil movements, Journal of Geotechnical and Geoenvironmental Engineering, 123, no. 9, pp 792-801.

Guo, W. D. (2013) Pu-Based Solutions for Slope Stabilizing Piles, International Journal of Geomechanics, 13, no. 3, pp 292-310.

Guo, W. D. and Lee, F. H. (2001) Load transfer approach for laterally loaded piles, International Journal for Numerical and Analytical Methods in Geomechanics, 25, no. 11, pp 1101-1129.

Hong, W.-P. and Lee, K.-W. (2009) Evaluation of Lateral Movement of Piled Bridge Abutment Undergoing Lateral Soil Movement in Soft Ground, Marine Georesources & Geotechnology, 27, no. 3, pp 177-189.

Hungr, O., Leroueil, S. and Picarelli, L. (2014) The Varnes classification of landslide types, an update, Landslides, 11, pp 167-194.

Ismael, A., Gunal, M. and Hussein, H. (2015) Effect of Bridge Pier Position on Scour Reduction According to Flow Direction, Arabian Journal for Science and Engineering, 40, no. 6, pp 1579-1590.

Jardine, R. J., Potts, D. M., Fourie, A. B. and Burland, J. B. (1986) Studies of the influence of non-linear stress–strain characteristics in soil–structure interaction, Géotechnique, 36, no. 3, pp 377-396.

Jeong, S., Kim, B., Won, J. and Lee, J. (2003) Uncoupled analysis of stabilizing piles in weathered slopes, Computers and Geotechnics, 30, no. 8, pp 671-682.

Jia, G. W., Zhan, T. L. T., Chen, Y. M. and Fredlund, D. G. (2009) Performance of a large-scale slope model subjected to rising and lowering water levels, Engineering Geology, 106, no. 1-2, pp 92-103.

Johansson, J. M. A. and Edeskar, T. (2014) Effects of external water-level fluctuations on slope stability, Electronic Journal of Geotechnical Engineering, 19 K, pp 2437-2463.

Jye, L. L., Kaniraj, S. R. and Taib, S. N. L. (2014). Effect of Tidal Fluctuation on Ground Movement and Pore Water Pressure Lee "Proceedings of the Geo-Shanghai 2014 International Conference", 2014 Shanghai. ASCE, pp 35-44.

Kelesoglu, M. K. and Cinicioglu, S. F. (2010) Free-Field Measurements to Disclose Lateral Reaction Mechanism of Piles Subjected to Soil Movements, Journal of Geotechnical and Geoenvironmental Engineering, 136, no. 2, pp 331-343.

Kim, Y. and Jeong, S. (2011) Analysis of soil resistance on laterally loaded piles based on 3D soil–pile interaction, Computers and Geotechnics, 38, no. 2, pp 248-257.

Kourkoulis, R., Gelagoti, F., Anastasopoulos, I. and Gazetas, G. (2011) Slope Stabilizing Piles and Pile-Groups: Parametric Study and Design Insights, Journal of Geotechnical and Geoenvironmental Engineering, 137, no. 7, pp 663-677.

Kw An, R. T. F. and Melville, B. W. (1994) Local scour and flow measurements at bridge abutments, Journal of Hydraulic Research, 32, no. 5, pp 661-673.

Leong, E. C. and Rahardjo, H. (1997) Review of Soil-Water Characteristic Curve Equations, Journal of Geotechnical and Geoenvironmental Engineering, 123, no. 12, pp 1106-1117.

Leroueil, S. and Picarelli, L. (2012) Assessment of Slope Stability, Geotechnical Engineering State of the Art and Practice@ sKeynote Lectures from GeoCongress 2012, 1, pp 122-156.

Leung, C. F. (2006) Performance of piles subject to soil movements, Physical Modelling in Geotechnics, 6th ICPMG'06 - Proceedings of the 6th International Conference on Physical Modelling in Geotechnics, 1-2, pp 87-98.

Li, F., Han, J. and Lin, C. (2013) Effect of Scour on the Behavior of Laterally Loaded Single Piles in Marine Clay, Marine Georesources & Geotechnology, 31, no. 3, pp 271-289.

Li, S. and Feng, X. (2008) Numerical analysis of slope stability influenced by varying water conditions in the reservoir area of the Three Gorges , China, pp 803-807.

Lirer, S. (2012) Landslide stabilizing piles: Experimental evidences and numerical interpretation, Engineering Geology, 149-150, pp 70-77.

López-Acosta, N. P., Auvinet, G. and Lezama, J. L. (2010) Study of Transient Flow Caused by Rapid Filling and Drawdown in Protection Levees, Scour and Erosion, 2010, pp 316-325.

Melville, B. W. (2006) Bridge abutment scour: estimation and protection, Australian Journal of Water Resources, 10, no. 1, pp 81-92.

Meyer, B. J. and Reese, L. C. (1979). Analysis of Single Piles Under Lateral Loading ", 1979.

Moregenstern, N. (1963) Stability Charts for Earth Slopes During Rapid Drawdown, Géotechnique, 13, no. 2, pp 121-131.

Ng, K. W., Chakradhar, R., Ettema, R. and Kempema, E. W. (2015) Geotechnical considerations in hydraulic modeling of bridge abutment scour, Journal of Applied Water Engineering and Research, 3, no. 2, pp 132-142.

Ong, D. E. L., Leung, C. F., Chow, Y. K. and Ng, T. G. (2015) Severe Damage of a Pile Group due to Slope Failure, Journal of Geotechnical and Geoenvironmental Engineering, 141, no. 5, pp 04015014.

Pan, J. L., Goh, A. T. C., Wong, K. S. and Teh, C. I. (2002) Ultimate Soil Pressures for Piles Subjected to Lateral Soil Movements, Journal of Geotechnical and Geoenvironmental Engineering, 128, no. 6, pp 530-535.

Papanicolaou, A., Sutarto, T., Wilson, C. and Langendoen, E. (2014) Bank Stability Analysis for Fluvial Erosion and Mass Failure.- "World Environmental and Water Resources Congress 2014", pp 1497-1508. American Society of Civil Engineers.

Picarelli, L., Urciuoli, G. and Russo, C. (2004) Effect of groundwater regime on the behaviour of clayey slopes, Canadian Geotechnical Journal, 41, no. 3, pp 467-484.

Pizzuto, J. E. (2008) Streambank Erosion and River Width Adjustment, Sedimentation Engineering, pp 387-438.

Poulos, H. G. (1973) Analysis of piles in soil undergoing lateral movement, Journal of the soil mechanics and foundations division, 11, pp A171-A171.

Qin, H. and Guo, W. D. (2012) Group Effects of Piles Due To Lateral Soil Movements, Second International Conference on Geotechnique, Construction Materials and Environment, pp 1-4.

Rinaldi, M., Casagli, N., Dapporto, S. and Gargini, A. (2004) Monitoring and modelling of pore water pressure changes and riverbank stability during flow events, Earth Surface Processes and Landforms, 29, no. 2, pp 237-254.

Rinaldi, M. and Darby, S. E. (2007) Modelling river-bank-erosion processes and mass failure mechanisms: progress towards fully coupled simulations, Developments in Earth Surface Processes, 11, pp 213-239.

Rinaldi, M., Mengoni, B., Luppi, L., Darby, S. E. and Mosselman, E. (2008) Numerical simulation of hydrodynamics and bank erosion in a river bend, Water Resources Research, 44, no. 9, pp 1-17.

Rinaldi, M. and Nardi, L. (2013) Modeling Interactions between Riverbank Hydrology and Mass Failures, Journal of Hydraulic Engineering, 18, pp 1231-1240.

Sawant, V. A. and Shukla, S. K. (2012) Three-Dimensional Finite Element Analysis of Laterally Loaded Piles in Sloping Ground, Indian Geotechnical Journal, 42, pp 278-286.

Shaojun, L. I., Knappett, J. and Xiating, F. (2015) Investigation of Slope Stability Influenced by Change of Reservoir Water Level in Three Gorges of China, Physical and Numerical Simulation of Geotechnical Engineering, d, no. 18, pp 49-55.

Song, K., Yan, E., Zhang, G., Lu, S. and Yi, Q. (2015) Effect of hydraulic properties of soil and fluctuation velocity of reservoir water on landslide stability, Environmental Earth Sciences, 74, no. 6, pp 5319-5329.

Song, Y.-S., Hong, W.-P. and Woo, K.-S. (2012) Behavior and analysis of stabilizing piles installed in a cut slope during heavy rainfall, Engineering Geology, 129-130, pp 56-67.

Stewart, D. P., Jewell, R. J. and Randolph, M. F. (1993) Numerical modelling of piled bridge abutments on soft ground, Computers and Geotechnics, 15, no. 1, pp 21-46.

Sullivan, R. A. (1972) Behavior of wharf by effected of river fluctations, Journal of the Soil Mechanics and Foundation Division, 98, pp 939-954.

Sun, J.-C. and Wang, G.-Q. (2008) Inclined free face riverbank collapse by river scouring, pp 1627-1632.

Take, W. A. and Bolton, M. D. (2011) Seasonal ratcheting and softening in clay slopes, leading to first-time failure, Géotechnique, 61, no. 9, pp 757-769.

Thomas, J. E. and Margeson, G. (2001) Impacts of Sediment Mounds under Pile Supported Wharf Structures.- "Ports '01", pp 1-11. American Society of Civil Engineers.

Thomas, J. E. and Morin, W. J. (2000) Wharf Movements Due to Tidal Fluctuations, Geotechnical Measurements, pp 109-125.

Urciuoli, G., Picarelli, L. and Leroueil, S. (2007) Local soil failure before general slope failure, Geotechnical and Geological Engineering, 25, no. 1, pp 103-122.

VandenBerge, D. R., Duncan, J. M. and Brandon, T. L. (2015) Limitations of Transient Seepage Analyses for Calculating Pore Pressures during External Water Level Changes, Journal of Geotechnical and Geoenvironmental Engineering, 141, no. 5, pp 04015005.

Wang, J.-J., Zhang, H.-P., Zhang, L. and Liang, Y. (2012) Experimental study on heterogeneous slope responses to drawdown, Engineering Geology, 147-148, pp 52-56.

Wang, L. P. and Zhang, G. (2013) Progressive failure behavior of pile-reinforced clay slopes under surface load conditions, Environmental Earth Sciences, 71, no. 12, pp 5007-5016.

Won, J., You, K., Jeong, S. and Kim, S. (2005) Coupled effects in stability analysis of pile–slope systems, Computers and Geotechnics, 32, no. 4, pp 304-315.

Yan, Z.-L., Wang, J.-J. and Chai, H.-J. (2010) Influence of water level fluctuation on phreatic line in silty soil model slope, Engineering Geology, 113, no. 1-4, pp 90-98.

Zhan, T. L. T., Zhang, W. J. and Chen, Y. M. (2006) Influence of Reservoir Level Change on Slope Stability of a Silty Soil Bank, The Fourth International Conference on Unsaturated Soils, ASCE, April 2–4, no. 0086, pp 463-472.

Zhou, C., Shao, W. and van Westen, C. J. (2014) Comparing two methods to estimate lateral force acting on stabilizing piles for a landslide in the Three Gorges Reservoir, China, Engineering Geology, 173, pp 41-53.