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ORIGINAL ARTICLE

Conjunction effect of stream water level and groundwater flow for riverbank stability analysis

Shih-Wei Chiang · Tung-Lin Tsai · Jinn-Chuang Yang

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Abstract Variations in pore-water pressure determined by the groundwater table within a riverbank have been investigated and recognized as an essential factor in determining riverbank stability with respect to mass failure. However, the effect of pore-water pressure is taken into account for most of the existing riverbank stability models under some simplified assumptions, and the limitations of predicting ability may arise. To avoid the unrealistic estimation of pore-water pressure distribution, the new approach proposed here is to couple riverbank stability with groundwater flow modeling, and apply this to tackle the conjunction effect between river stage and groundwater table. Moreover, riverbank material characteristics and the influence of infiltration can be taken into consideration via groundwater flow modeling. Two hypothetical examples, stage rising and stage falling, are used to investigate the capabilities of the present study and two representative methods. The simulated results show that riverbank failure is triggered particularly during the falling stage, which has been pointed out by other researchers as well. Furthermore, the riverbank material characteristics predominantly control the occurrence of failure and should be considered regarding assessment of riverbank stability. Additionally, the effects of parameters indicate that riverbanks with soil properties of low permeability or high specific yield with great infiltration intensity during the falling stage have a tendency to riverbank failure.

Keywords Riverbank stability · Groundwater flow · Pore-water pressure · Stream water level

S.-W. Chiang · J.-C. Yang
Department of Civil Engineering, Disaster Prevention and Water Environment Research Center, National Chiao Tung University, 1001 Ta Hsueh Road, Hsinchu 30010, Taiwan

T.-L. Tsai (✉)
Department of Civil and Water Resources Engineering, National Chiayi University, 300 Syuefu Road, Chiayi 60004, Taiwan
e-mail: tltsai@mail.ncyu.edu.tw

List of symbols

c	A constant value (approximately 1.12)
c'	Effective cohesion
FS	Safety factor
H	Bank height
$H_0(x)$	Initial height of water table across the flow domain
$H_1(t)$ and $H_2(t)$	Time fluctuating height of water table at the boundaries
H_w	River stage
h	Height of water table
I	Recharge rate from infiltration
K	Hydraulic conductivity
L	Length of the failure plane
l	Length of the aquifer
S	Specific yield
t	Time coordinates
V_w	Rising or falling velocity of the river stage
x	Space coordinates
α	Angle of riverbank
β	Failure plane angle
ϕ'	Effective friction angle of the soil
ϕ^b	Angle used to determine the rate of increase in shear strength due to increasing matric suction

Introduction

Steep riverbanks composed of cohesive materials tend to fail in block sliding along planar failure planes (Thorne 1982; Osman and Thorne 1988; Darby et al. 2000). Over the past decades, the stability of riverbanks with respect to mass failure has usually been analyzed based upon the limit equilibrium method because of its simplicity and because much experience has been accumulated. Generally, the stability condition is presented as the safety factor (FS) equal to the ratio of resisting force to driving force acting on the failure plane, and failure can be predicted to take place when the FS is lower than 1.

Many riverbank stability studies adopting simple solutions have been extensively applied to riverbanks (Lohnes and Handy 1968; Spangler and Handy 1973; Osman and Thorne 1988; Thorne and Abt 1993). In these studies, the weight of the failure block was the dominant force to determine the FS. For further understanding of the response of water pressure to the stability conditions, several researchers have considered the effect of river stage and groundwater table, i.e., pore-water pressure and confining pressure, in the analyses, for example, Simon et al. (1991), Darby and Thorne (1996) and Darby et al. (2000). However, these typical models used traditional theories of saturated soil mechanics; the effect of negative pore-water pressure (matric suction) on riverbank stability was ignored. In case of low groundwater levels, the potential failure plane may pass through the unsaturated portion of soil, and negative pore-water pressure can play an important role in the estimation of the FS. In order to improve this shortcoming, the extended Mohr-Coulomb failure principle (Fredlund and Rahardjo 1993) was employed to deal with unsaturated soil mechanics, and the influence of soil matric suction was recognized as a significant factor to determine the stability state in the subsequent works, e.g., Simon and Curini (1998), Rinaldi and Casagli (1999), Simon et al. (2000) and Simon and Thomas (2002).

Although a large number of comprehensive riverbank stability models have been developed, most of them still have some limitations that need to be overcome. For example, the groundwater table is supposed to be horizontal and maintain a constant elevation throughout the whole domain of the riverbank. In addition, the groundwater table is not related to river stage, which means that a discontinuous water surface profile may exist adjacent to the riverbank, and interaction cannot be taken into account. However, the groundwater table may have spatial and temporal variation induced by various factors and cannot remain unchanged in reality. Therefore, the existing models generally apply some simplified hypotheses to the river stage and groundwater level in order to be able to evaluate riverbank stability conditions, but this is unrealistic.

In this study, further refinements including the effect of groundwater table fluctuation and the interaction between river stage and groundwater table are implemented by combining stability analysis with groundwater flow computation. In the following sections, first formulations for both groundwater flow modeling and riverbank stability are described briefly. Subsequently, a capability demonstration involving two representative methods is proposed, and the differences of predictive abilities between them and the present study are then discussed. Finally, the effects of parameters of the riverbank stability model are examined with several hypothetical cases.

Framework of the riverbank stability analysis

Groundwater flow modeling

The unsteady groundwater flow problem involving a changing free surface can be governed by a one-dimensional Boussinesq's equation with a local rectangular Cartesian coordinate system (Harr 1962; Bear 1972), as shown in Fig. 1. The governing equation can be written as follows:

$$S\frac{\partial h}{\partial t} = K\frac{\partial}{\partial x}\left(h\frac{\partial h}{\partial x}\right) + I \qquad 0 \le x \le l \tag{1}$$

$$h(0,t) = H_1(t) \tag{2}$$

$$h(l,t) = H_2(t) \tag{3}$$

$$h(x,0) = H_0(x) \tag{4}$$

where S is the specific yield; h is the height of the water table; K is the hydraulic conductivity; I is the recharge rate from infiltration; x and t are the space and the time coordinates; l is the length of the flow domain. $H_1(t)$ and $H_2(t)$ are the time fluctuating heights of the water table at the boundaries, and $H_0(x)$ is the initial height of the water table across the flow domain.

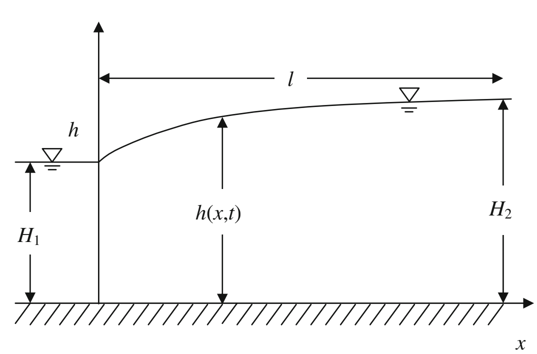

Fig. 1 Schematic diagram of the groundwater table profile

Analytical solutions are available only for problems with very simple boundary conditions. Thus, the fully implicit finite difference method is applied herein, and the formulation for the governing equation can be written as:

$$v = h^2 \tag{5}$$

$$\frac{S}{2\sqrt{v_i^n}}\left(\frac{v_i^{n+1} - v_i^n}{\Delta t}\right) - \frac{K}{2}\left(\frac{v_{i+1}^{n+1} - 2v_i^{n+1} + v_{i-1}^{n+1}}{\Delta x^2}\right) = I \tag{6}$$

The height of the groundwater table h can be computed from Eqs. 5 and 6, so the profile of the groundwater table within the riverbank can be obtained. However, one cannot know the pore-water pressure exerted at any position of the riverbank depending only on the groundwater table; therefore, a solution presented in the studies of Rinaldi and Casagli (1999) and Simon et al. (2000) is based on the following simplifying hypotheses: Pore-water pressure varies hydrostatically with distance above or below the groundwater table. That is, pore-water pressure is negative and decreases linearly above the groundwater table, and conversely below the groundwater table pore-water pressure is positive and increases linearly. The same procedure to estimate the distribution of pore-water pressure is also used in this study.

Riverbank stability formulation

Once the groundwater table is computed from the groundwater modeling mentioned above, the riverbank failure potential can be predicted using the stability analysis. A riverbank stability analysis algorithm, based on the limit equilibrium method, which accounts for forces acting on the failure plane because of the groundwater level and river stage, has been proposed by several previous researchers, such as Osman and Thorne (1988), Darby and Thorne (1996), Casagli et al. (1999), Rinaldi and Casagli (1999), Simon et al. (2000) and Simon and Thomas (2002). As shown in Fig. 2, forces considered for riverbank stability analysis include: (1) the weight of the failure block (W), (2) the hydrostatic uplift force on the saturated portion of the failure plane (U), (3) the hydrostatic confining force provided by the stream water (P) and (4) the matric suction force on the unsaturated portion of the failure plane (S).

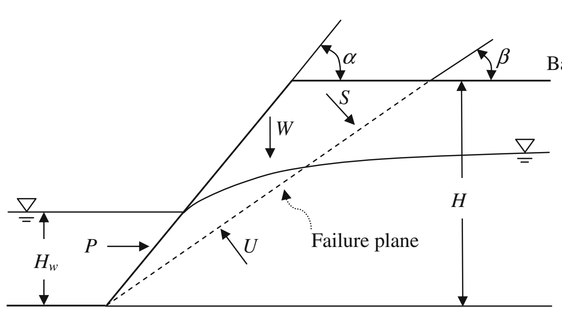

Fig. 2 Conceptual diagram of the riverbank and the forces considered in Eq. 7

Riverank stability can be evaluated by the factor of safety (FS) expressed by:

$$\mathrm{FS} = \frac{c'L + S\tan\phi^b + [W\cos\beta + P\cos(\alpha - \beta) - U]\tan\phi'}{W\sin\beta - P\sin(\alpha - \beta)} \tag{7}$$

where c' is the effective cohesion; L is the length of the failure plane; ϕ^b is the angle used to determine the rate of increase in shear strength due to increasing matric suction; β is the failure plane angle; α is the angle of riverbank; ϕ' is the effective friction angle of the soil.

To apply Eq. 7, it is necessary to define the failure plane angle first in order to determine the weight of the failure block and the length of the failure plane. Lohnes and Handy (1968) and Spangler and Handy (1973) both used Eq. 8 to estimate the failure plane angle. The same approach is also used in the present study.

$$\beta = \frac{1}{2}(\alpha + \phi') \tag{8}$$

By Eq. 7, the FS can be adopted to determine a given riverbank to be at a stable state when FS > 1.0, a critical state when FS = 1.0 and an unstable state when FS < 1.0, respectively.

In Eq. 7, the hydrostatic uplift force U is calculated from the area of the distribution of positive pore-water pressure on the basis of the profile of the groundwater table under the hydrostatical distribution hypothesis mentioned earlier. Similarly, the matric suction force S can be determined by negative pore-water pressure. The hydrostatic confining force P is provided by the river stage, which is also the boundary condition regarding the groundwater modeling. Therefore, these three fundamental forces can be determined by groundwater flow computation, and the combined effect is incorporated into the FS algorithm.

Capability demonstration

Category of analysis method

In this section, several selected analysis methods are categorized as two groups based on their capabilities in terms of forces encountered to test the predictive abilities. The main features of these methods have been described previously and are summarized in Table 1. Obviously, the listed rank of these methods corresponds to the amounts of considered forces. It should be noted that the methods in the second group even take all four forces into

Table 1 Summary of properties of bank stability analyses for comparison

Analysis method	Failure block weight	Hydrostatic uplift force	Hydrostatic confining force	Matric suction force	Groundwater flow	Infiltration
1st group						
Simon et al. (1991), Darby and Thorne (1996), Darby et al. (2000)	Yes	Yes	Yes	No	No	No
2nd group						
Simon and Curini (1998), Rinaldi and Casagli (1999), Simon et al. (2000), Simon and Thomas (2002)	Yes	Yes	Yes	Yes	No	No
The present study	Yes	Yes	Yes	Yes	Yes	Yes

consideration, but the computation of groundwater flow cannot be accomplished.

Description of test conditions

Two individual hypothetical examples, river rising and falling stages with riverbank height $H = 3$ m, are employed to investigate FS variation with the following parameters: $\alpha = 60°$, $\gamma_s = 18$ kN/m^3, $c' = 3$ kPa, $\phi' = 33°$, $\phi^b = 16°$, $S = 0.2$ and $K = 10^{-5}$ m/s. Applying groundwater modeling, two boundary conditions and one initial condition shown in Eqs. 2–4 are needed. A stage hydrograph is imposed as one of the boundary conditions, which varies linearly from 0.6 to 2.4 m with respect to time and lasts for 4 h. Another one is set to be the no-flux condition $\left(\frac{\partial h(l,t)}{\partial x} = 0\right)$, and a flow domain length of 30 m is used in the simulation. The initial groundwater surface profile is assumed to be equal to the incipient river stage.

For the methods in the first and second groups, a simplified approach presented by Rinaldi and Casagli (1999) is used in the simulation in order to assess the impact of river stage variation on the stability state. The process is the following: (1) during the rising stage, the groundwater level reaches an immediate equilibrium with the river stage; (2) during the falling stage, the groundwater level remains suspended at the level reached during the rising stage.

Results and discussion

Values of FS computed by various methods with respect to a ratio of the river stage H_w normalized by the bank height H during the rising and falling stages of the flow events are shown in Figs. 3a and b, respectively. Figure 3a reveals that compared with the second group, the first group has the minimum values of FS and may greatly underestimate the riverbank stability, especially at the beginning process of the rising stage. This outcome highlights the great impact of matric suction on riverbank stability, particularly at low groundwater levels. In addition, the distinction between the simulated results of the first and second groups gradually decreases with the increase in H_w/H because the benefit of matric suction on riverbank stability diminishes with rising groundwater levels, which causes a reduction in the FS.

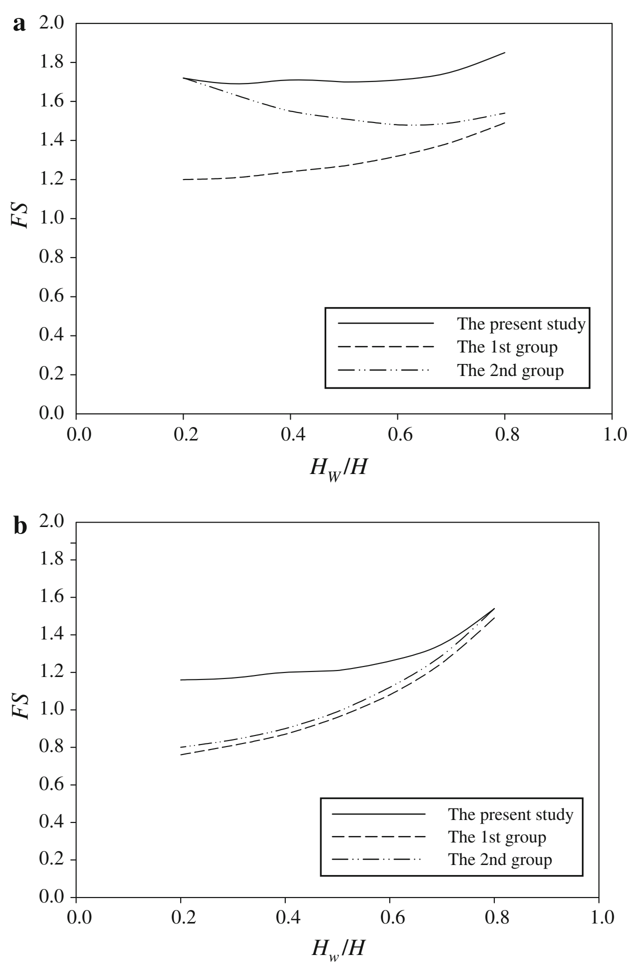

Fig. 3 a FS variations as a function of H_w/H with different analysis methods during the rising stage. b FS variations as a function of H_w/H with different analysis methods during the falling stage

However, Fig. 3a illustrates that the FS fluctuates and increases slightly with respect to H_w/H in the present study. This can be explained by Eq. 7 in which the hydrostatic uplift force makes the FS reduce, whereas the matric suction force and the hydrostatic confining force both generate an increase in FS. Accordingly, the FS may decrease or increase during the rising stage depending on whether the hydrostatic confining force counteracts the combined effect of the hydrostatic uplift force and the matric suction force. In this case, the river stage could likely rise at a sufficiently faster rate than the groundwater level, which improves the FS with the rising stage. Regarding the falling stage, it should be noted from Fig. 3b that the value of FS computed in the present study is greater than 1, whereas the riverbank failure is simulated by the other two group methods. This means that the first and second groups predict that the riverbanks are equally or less stable than in the analysis presented by this study since the groundwater level is assumed to be maintained at the level reached, i.e., the highest level with respect to the falling stage.

For further understanding of the effect of river stage on riverbank stability, an attempt to simulate the process of FS variation with time was made using three complete stage hydrographs (triangular type lasting for 24 h); the results are shown in detail in Fig. 4. Figure 4 indicates that various values of the final FS can be obtained by this study, whereas the other methods produce the same results in spite of the pattern of the hydrograph because of the unavailability of a realistic transient process of pore-water pressure. Accordingly, computing groundwater flow is quite necessary since it not only takes the material properties of the riverbank into consideration, but also has the ability to present river stage variation in order to provide reasonable values of FS.

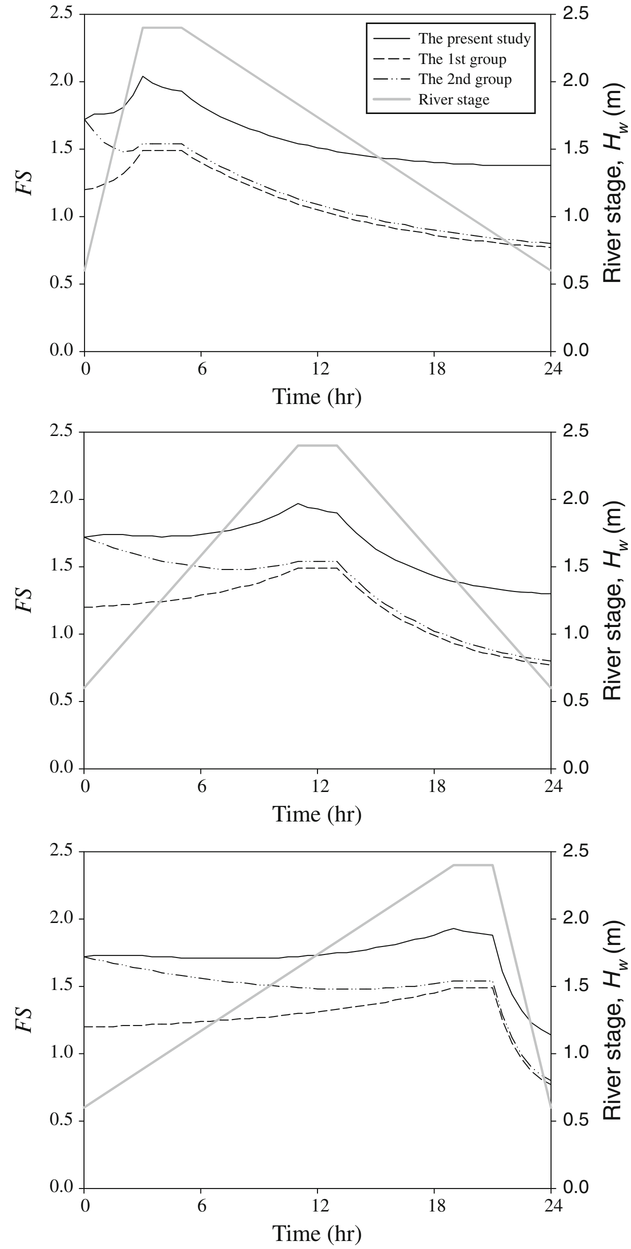

Fig. 4 Results of FS variations with time for three selected river stage hydrographs

Effects of parameters

Effect of hydraulic conductivity

With all other parameters remaining the same as in the previous section, using a K of 10^{-4}, 10^{-5} and 10^{-6} m/s, respectively, the simulated results of the groundwater table are shown in Fig. 5. Figure 5a illustrates the variation of the groundwater table during the rising stage from 0.6 to 2.4 m. One can clearly observe from Fig. 5a that the higher groundwater level can be obtained with greater values of K. The upper and the lower sets of curves in Fig. 6 show the variation of FS with respect to H_w/H during the rising and falling stages, respectively. As to the rising stage, one can observe from Fig. 6 that FS vibrates from about 1.72 and reaches the maximum values at the end of the flow event with Ks of 10^{-5} and 10^{-6} m/s. The reason is that a higher river stage producing a greater confining force causes strong resistance to the riverbank with a lower groundwater level induced by a smaller value of K. During the falling stage, the FS suddenly reduces below 1 with a K of 10^{-6} m/s. It indicates that the water confined in the riverbank with small values of K cannot be drained immediately (see Fig. 5b), and both the hydrostatic uplift force and the matric suction force may remain nearly unchanged, but the confining force drops abruptly so as to induce eventual failure. Therefore, one can conclude that the worst stability

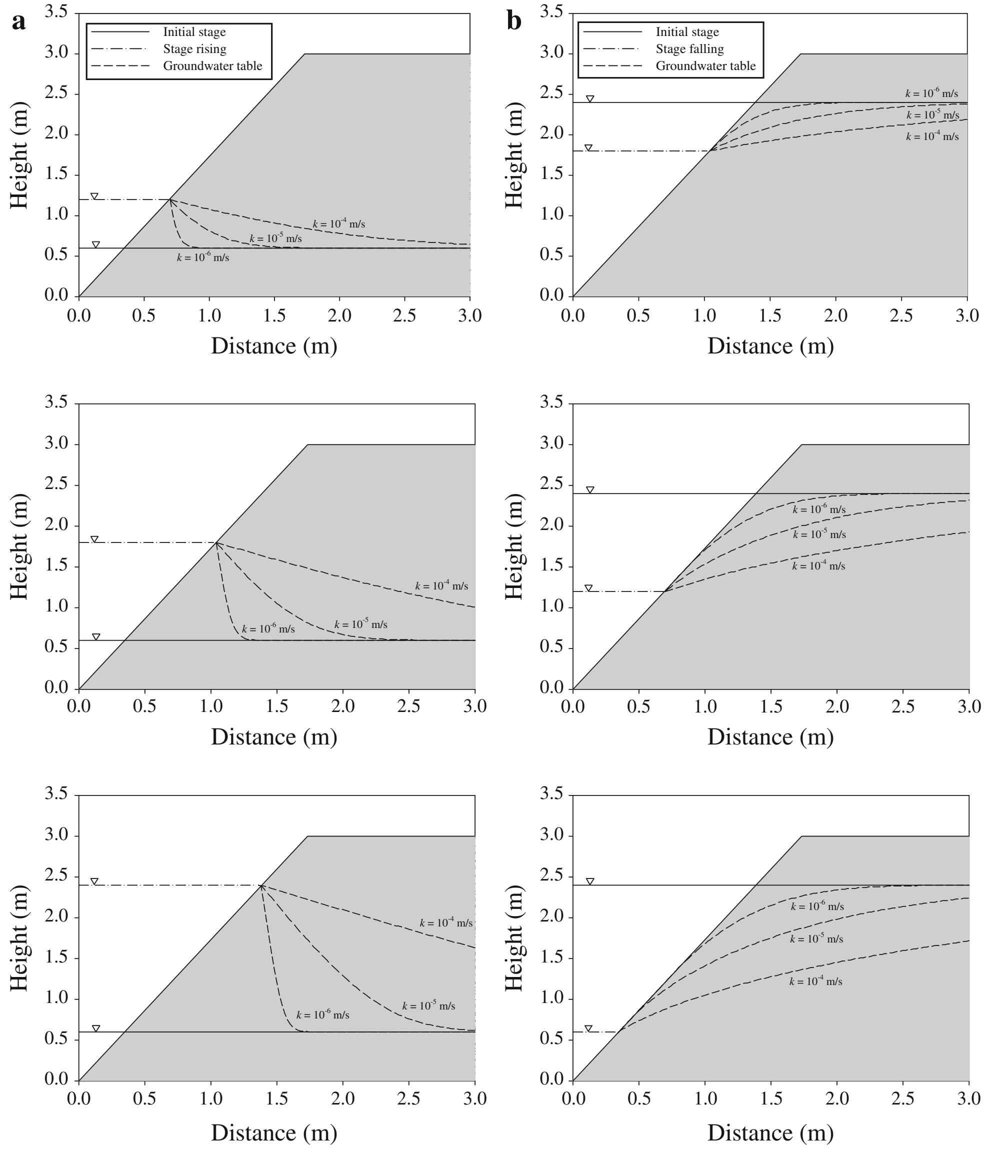

Fig. 5 River stage and variation of groundwater table from modeling with various *K*s for flow events: **a** during the rising stage; **b** during the falling stage

condition may occur once a low river stage coincides with a high groundwater level. In addition, the variations of FS with respect to the H_w/H ratio during the falling stage are larger than those during the rising stage. In other words, the parameter *K* is more sensitive with regard to the riverbank stability during the falling stage.

Effect of specific yield

Specific yield *S*, the ratio of the volume of water drained by gravity after saturation to the soil volume, is another major parameter with regard to groundwater modeling. Repeating an analysis similar to the one mentioned above, representative values of *S* of 0.05, 0.1, 0.2 and 0.3 are adopted to examine FS variations with H_w/H under the conditions of rising and falling stages. The simulated results shown in Fig. 7 indicate that FS fluctuates in a narrow range during the rising stage, which means that specific yield has few effects on riverbank stability. Figure 7 also shows that riverbanks with larger values of *S* reveal more instability during the falling stage. The reason may be because the higher *S* causes a greater amount of water to be contained within the riverbank, which needs more time to be released and leads to a higher elevation in the groundwater table. As far as the effect of parameters is concerned, soil material of riverbanks is quite an important factor when applying the riverbank stability analysis.

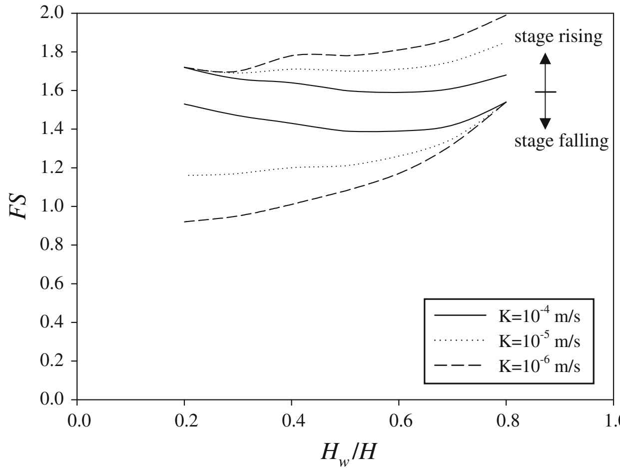

Fig. 6 FS variations as a function of H_w/H with different *K*s during the rising and falling stages

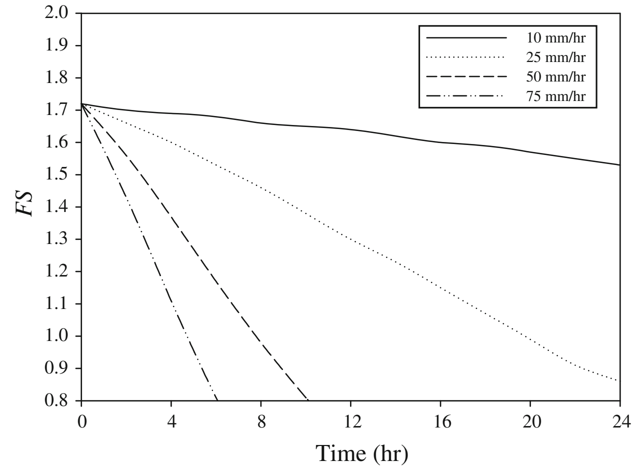

Fig. 8 The change of the FS with respect to time for different infiltration intensities

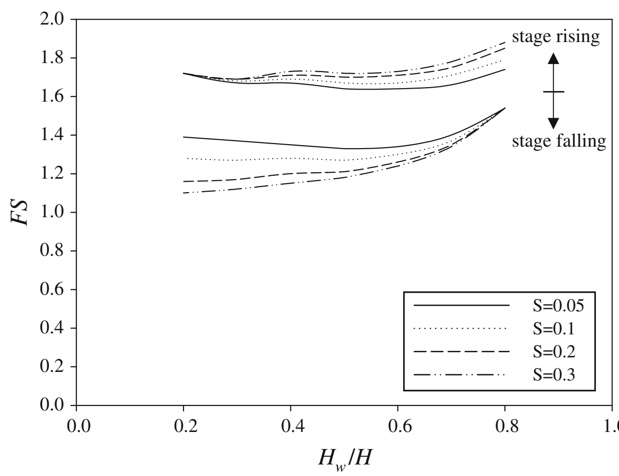

Fig. 7 FS variations as a function of H_w/H with different *S*s during the rising and falling stages

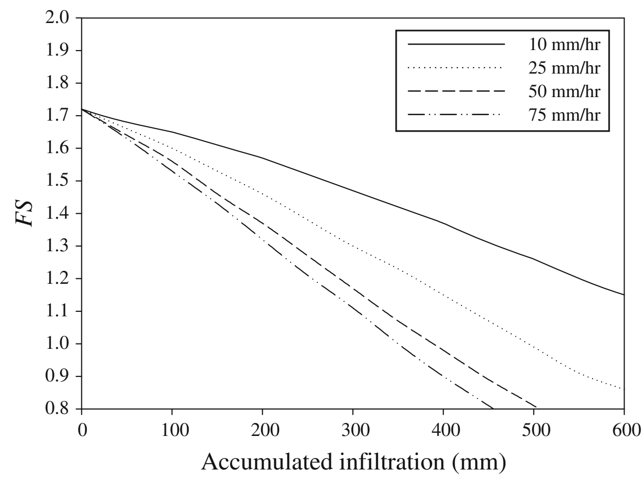

Fig. 9 The change of FS with respect to accumulated infiltration for different infiltration intensities

Effect of infiltration

Four cases with various infiltration intensities uniformly distributed at 10, 25, 50 and 75 mm/h are studied in this simulation when the river stage is fixed at 0.6 m, and the other parameters are the same as in the previous analyses. The simulated FS variations with respect to time and accumulated infiltration are shown in Figs. 8 and 9, respectively. One can clearly see from Figs. 8 and 9 that FS decreases approximately linearly with the increase of both time and accumulated infiltration. Within the first 24 h, riverbank failure occurs after about 4.6, 7.5 and 19 h with infiltration intensities of 75, 50 and 25 mm/h when the accumulated infiltration reaches 345, 375 and 475 mm, respectively. However, the *FS* gradually varies from 1.72 to 1.53 during the period of infiltration with an intensity of 10 mm/h, and failure is not triggered at the end of the event. Furthermore, it should be noted from Fig. 9 that the riverbank may be at a stable condition (FS > 1) or at an unstable condition (FS < 1) even with the same cumulative infiltration. Hence, one may conclude that great infiltration intensity is apt to cause riverbank failure.

Effect of the rate of river stage variation

From the results simulated earlier, one can determine that the fluctuation of river stage has a great effect on riverbank stability. The evaluation of how the rate of stage variation V_w influences the bank stability during rising and falling stages becomes an important task for river training projects. As shown in Fig. 10, various values of V_w, 0.05, 0.1, 0.5, 1.0 and 2.0 m/h are chosen to examine the variations of FS with the ratio, H_w/H. With a focus on the falling stage

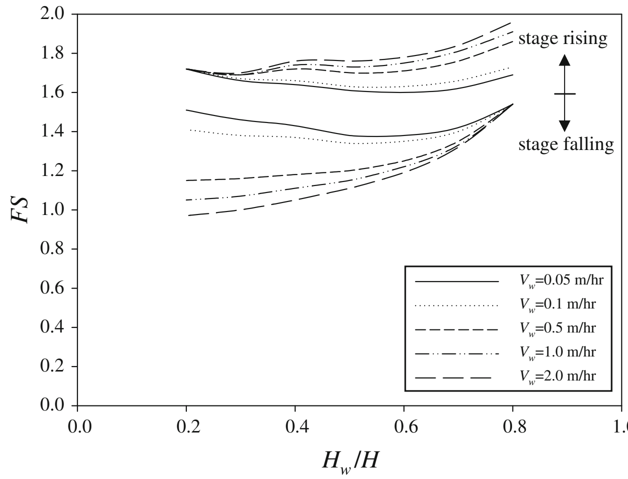

Fig. 10 FS variations as a function of H_w/H with different V_ws during the rising and falling stages

conditions, the FS continuously declines from 1.54, and failure is triggered specifically with V_w of 2.0 m/h since rapid drawdown of the river stage produces abrupt dropping of the hydrostatic confining force. Therefore, one can conclude from the simulation that the relationship between the groundwater table and the river stage plays an important role in the stability of riverbanks.

Conclusions

A large number of comprehensive riverbank stability models incorporating simplified hypotheses regarding pore-water pressure have been developed to investigate the effect of FS and applied to natural riverbank applications. The role and the importance of pore-water pressure have been recognized in determining riverbank stability with respect to mass failure. Hence, determining the precise groundwater table within the riverbank is quite essential.

Based on earlier developments, the new approach presented in this study has a combination of groundwater flow and stability analysis to obtain a more realistic groundwater table in order to define the effect of negative and positive pore-water pressures on riverbank stability. The advantage of this approach is that the effects of material properties of riverbanks and infiltration on pore-water pressure distribution are taken into account by applying groundwater modeling. Other researchers have previously proposed that bank failure is generally considered to occur particularly during the recession of hydrographs when the riverbank material is under nearly or totally saturated conditions. In addition, the effect of matric suction has a significant impact on riverbank stability and should be taken into consideration especially under lower groundwater level conditions. The simulated results presented in this study support and confirm these concepts on the basis of a series of analyses. According to the conclusions of the analyses, any factor can make the riverbank retain high groundwater levels relative to the river stage, such as riverbank material with low permeability or high specific yield; heavy infiltration and rapid stage falling have a tendency to make riverbanks unstable. Furthermore, it is concluded that riverbanks may have a wide range of stability conditions for different material properties of riverbanks and hydrographs. Riverbank failure may or may not occur depending on soil properties even during the falling stage. Consequently, particular attention needs to be paid to the material characteristics of banks because they not only determine shear strength, but directly influence groundwater table distribution. The approach presented here is more realistic and reasonable regarding groundwater levels and additionally has the ability to predict the occurrence time of failure and status in terms of riverbank stability.

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