Prediction of Mass Landslides of River Banks Subjected to Variations of the Water Level

Chhun Soksan, Ky Sambath, Martinez Juan, and Huynh Thanh Son

Abstract— *River bank stability is sensitive to the variation of the water level (WL) of the river. This is the case along the Lower Mekong River which WL change between dry and wet seasons is about 10m. For analyzing the risk of river banks slides a numerical analysis is performed using a finite difference discretization with respect to time and space that includes different simplified hypothesis. The Dupuit assumption of a unidirectional flow inside the soil is used to calculate the variation of the ground water table inside the bank. By using local hydrological data, three scenario are proposed to simulate the uncertainty of the initial ground water table condition. The mass sliding Safety Factor (SF) is predicted by a limit equilibrium method, i.e. the Fellenius slices method, with circular slip surfaces and relevant soil properties. The calculations demonstrate that the smallest minimum Safety Factor of mass slide occurs after a rapid drop of the WL. Moreover, the Safety factor decreases as the soil permeability is small. Furthermore, from the Safety Factors corresponding to slip lines emerging at different distances to the top of the bank, we determine a safety zone along the river that is useful for local risk management.*

Keywords— **Lower Mekong, slices method, safety factor, safety zone.**

1. INTRODUCTION

Landslides along Mekong River banks are problematic from many years with consequences that can be particularly severe, such as the collapse of structures and homes with occasional human victims. For example, In April 2008, in Reussey Keo district Phnom Penh, Cambodia, a zone about 50m long and 30m wide of Tonle Sap river bank was cut off and slid into water. As a consequence, 38 houses were lost, making more than 300 people homeless [1]. Another big landslide along Mekong River happened in March 2012 in Long Xuyen town, An Giang province, Vietnam, where 110m long of the riverbank slid down taking 22 houses and forcing hundreds of people to evacuate [2]. There are several triggering factors to the river bank stability such as: scouring, erosion, piping, the variation of ground water table and the variation of mechanical soil parameters between saturated and unsaturated conditions, etc. In the research works lead by Darby et al [3] and Hai [4], the coupling of three different phenomena is performed: (i) the calculation of the ground water table variations inside the bank soil in function of the water level variations, (ii) the calculation of the erosion of the river banks surface due to the threshold of the river discharge and (iii) the calculation of the mass stability of the bank by the general limit equilibrium method of slices. The scope of our work is to determine the safety factor of the river bank with respect to a mass slide, but in order to facilitate the simulations by the users, the three above phenomena are modeled in a unique code MEStab written in Matlab language [5]–[7]. In this program, the following assumptions are considered: (i) the groundwater table is calculated by using Dupuit's assumption of a unidirectional flow [5]; (ii) the erosion of the bank surface is modeled using the method proposed by Rinaldi et al [8] and by Simon et al [9] based on a critical shear stress of soil and water flow intensity; (iii) lastly a rigid-plastic soil behavior is assumed, characterized by its cohesion and its friction angle A general limit equilibrium method of slices with circular slip surfaces is developed to calculate the *Safety Factor* of the riverbank mass stability as a function of the river water level variation. In the following results, the erosion phenomenon is not considered. We focus on the effect of different rates of the water level variations on the bank stability. The validation of our model by the comparisons to other standard programs is also performed [7]. Moreover, a safety zone its determined by the distance to the top of the river bank.

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The first two authors are grateful to the French Ministry of Education and to the Association Universitaire de la Francophonie for giving them scholarships during their research studies.

2. METHODOLOGY AND MODELS

2.1. Ground Water Table Model

Ground water table variations in the bank soil are modeled considering a plane flow network orthogonal to the river direction with parallel potential lines and a hydrostatic pore pressure field (Dupuit's model). The corresponding differential equation is the following:

$$\frac{\partial H(X,t)}{\partial t} = \frac{k_0}{2n_0} \frac{\partial^2 H^2(X,t)}{\partial^2 X^2} \tag{1}$$

where $H(x, t)$ is the pressure head, X and t are the space and time variable respectively, k_o and n_o are the permeability and porosity of the soil respectively (Figure1).

The discretization of equation 1 by Taylor series is applied to calculate the ground water variation by an explicit finite difference method with respect to both space and time:

$$H(X,t+\Delta t) = H(X,t) + K\left[H^2(X+\Delta X,t) - 2H^2(X,t) + H^2(X-\Delta X,t)\right] \tag{2}$$

where $K = \frac{k_o}{2n_o}\frac{\Delta t}{\Delta X^2}$ is a coefficient to be smaller than a value K_{max} in order to obtain the stability of the calculation [5], ΔX and Δt are incrementals in space and time respectively.

The initial condition of ground water table, $H(X, t=0)$, is assumed to be arbitrarily horizontal or taken from site measurements.

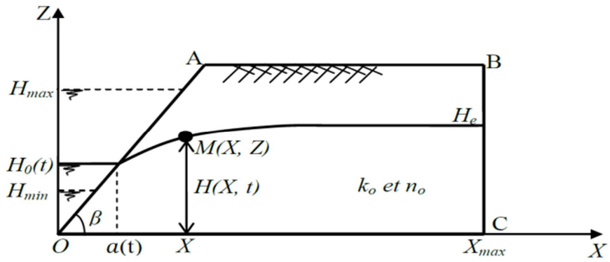

Fig. 1. Notations of ground water model.

The boundary condition along the bank (OA) corresponds to the variation of water level in the river over the time set:

$$H(a(t),t) = H_0(t) \tag{3}$$

The boundary condition for a distant vertical line (BC) of abscissa X_{max} corresponding to a nil transverse flow, is equivalent to a horizontal asymptote of the groundwater level:

$$H(X_{max},t) = H(X_{max} - \Delta X,t) \tag{4}$$

The comparison between simulation results and field measurements of the ground water table during tidal variations of the river water level allowed us to conclude that the Dupuit's simplified flow model can be adopted for bank soils possessing a homogeneous and isotropic permeability [5].

2.2. Slope Stability Model

From the usual equilibrium of slices (Figure 2) we can find out the projection of normal forces (equation 5) and tangential forces (equation 6) applied to the bottom of each slice:

$$N' = W\cos\alpha + P\cos(\beta - \alpha) - U \tag{5}$$

$$T_m = (W + P\cos\beta)\sin\alpha - P\sin\beta\cos\alpha \tag{6}$$

where N' is the effective normal force on the bottom of the slice, U is the resultant of the pore water pressure, W is the slice weight, P is the resultant of the water pressure at the surface of the slice, T_r is the shear resistance along the slice bottom, T_m is the applied shear force. The shear strength of each slice is calculated by the Coulomb plastic criterion:

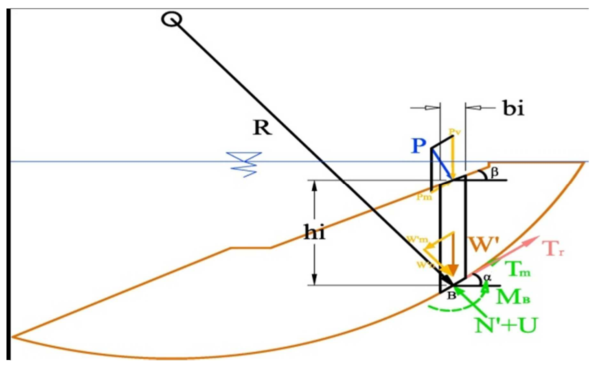

Fig. 2. Free body diagram of slip surface and slice with no inter-slice forces (Fellenius method).

$$T_r = C' + N'\tan\varphi' \tag{7}$$

where C' and φ' are the effective soil cohesion and friction angle respectively.

M_B is an additional moment for achievement of the moment equilibrium of each slice:

$$M_B = P(\sin\beta)h_i \tag{8}$$

For each slip surface, the *safety factor SF* is defined by the ratio of the resistant forces along the slip surface to the active forces applied to the soil mass (equation 9).

$$SF = \frac{\sum(C' + N'\tan\varphi')}{\sum[(W + P\cos\beta)\sin\alpha - P\sin\beta\cos\alpha]} \tag{9}$$

By considering different slip surfaces, the minimum value SF_{min} of SF is determined and defined as the safety factor of the bank.

3. APPLICATION TO THE STABILITY OF A LOWER MEKONG RIVER BANK

Figure 3 indicates the soil properties and the profile of a Mekong River bank near Kampong Cham city that were locally measured and tested in field and in laboratory [7]. The hydrological report of the water level at Kampong Cham city, measured by the Ministry of water resources and meteorology of Cambodia [10] is summarized on Table 1. The water level of the lower Mekong changes seasonally but it is not perfectly cyclic; the dry or the wet season sometimes arrives earlier or later. As the initial position of the ground water table is not known and the precipitation data in the immediate vicinity of the river bank is also unknown, three different cases of the river water level variation have been considered (Figure 4).

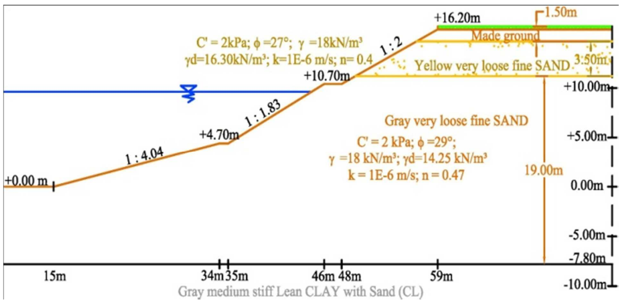

Fig.3. Mekong River bank geometry and soil properties (Kampong Cham)

Table 1 : Summary of Water Level variations at Kampong Cham

Mean Sea Level (MSL) (m)	-0.93
Flooding WL (m)	+16.11
Minimum WL (m)	+1.56
Ave. Max Climbing Speed (m/day)	+0.12
Ave. Max Dropping Speed (m/day)	-0.08
Max Climbing Speed in 2013 (m/day)	+0.77
Max Dropping Speed in 2013 (m/day)	-0.47

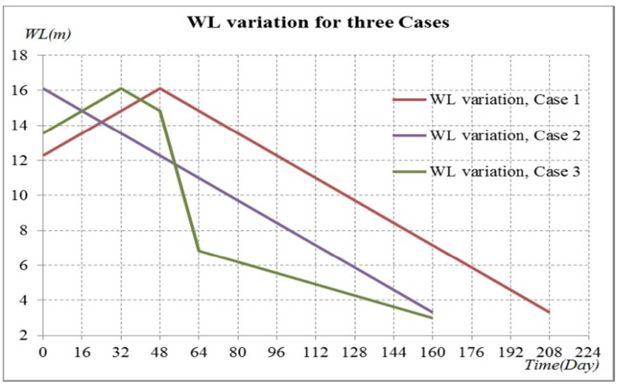

Fig. 4. WL variation scenario

Case 1: initial WL and water table are at elevation +12.27 m; then WL climbs up to +16.11 m and drops down to +3.31 m with an average speed 0.08 m/day during 208 days.

Case 2: initial WL and water table are at elevation maximum (+16.11 m); then WL drops down directly to +3.31 m with an average speed 0.08 m/day during 160 days.

Case 3: initial WL and water table are at elevation +13.55 m; then WL climbs up to 16.11 m and it drops to +14.83 m with an average speed 0.08 m/day, after that the dropping speed increases to 0.5 m/day (instantaneous dropping speed) during 16 days, then the speed slows down to 0.04 m/day until the WL reaches elevation +2.99 m. The total drop duration is 128 days.

The ground water variations simulated by MEStab code for the three cases are shown in Figures 5 to 7. The results show that, because of the low permeability of the soil, after more than a hundred days of drop down, in all cases the ground water table still remains quite high (equilibrium level) at about 20m far from the bank crest and quite close to the initial value.

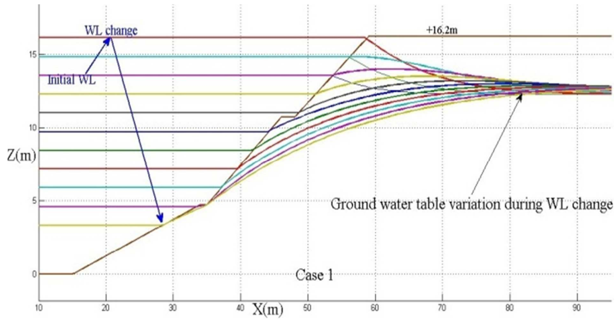

Fig. 5. Result of ground water variation (Case 1).

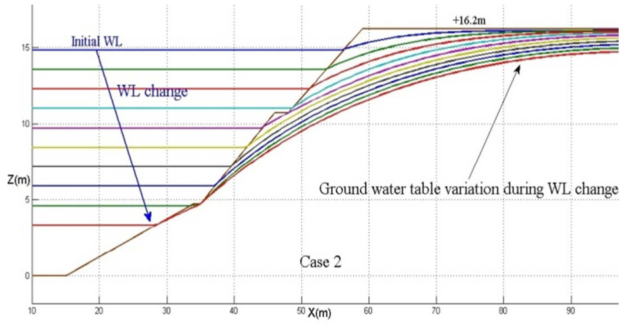

Fig. 6. Result of ground water variation (Case 2).

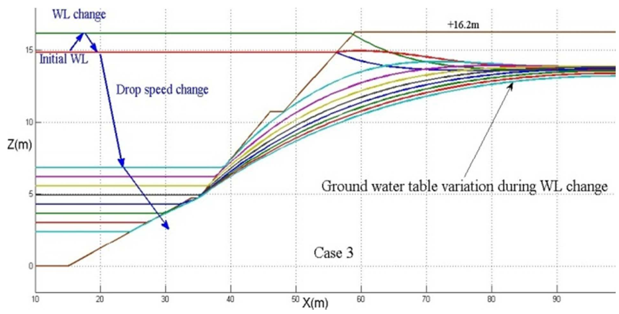

Fig. 7. Result of ground water variation (case 3)

By using the results of the ground water variation, the Safety Factors of the river bank have been calculated. Figures 8 to 10 show the results of the minimum Safety Factor SF_{min} for all cases as a function of WL. SF_{min} is calculated by MEStab code and by another standard program Slope-W®[11] which uses different assumptions of general limit equilibrium slices methods such as Bishop [12], Morgenstern and Price (M-P) [13] and Janbu [14].

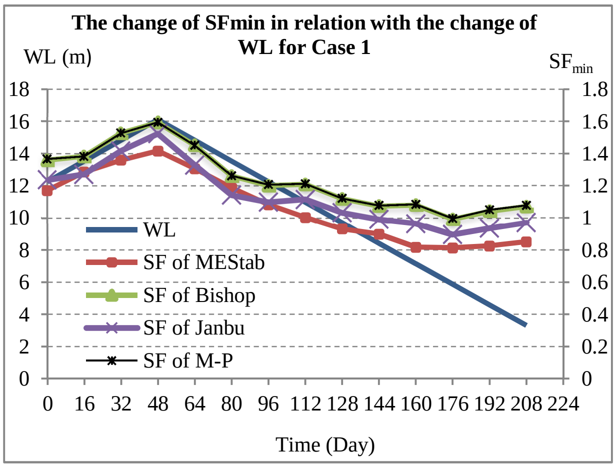

Fig.8. ***SF_{min}*** **calculated by MEStab and Slope-W for Case 1.** ***min[SF_{min}]=0.814***

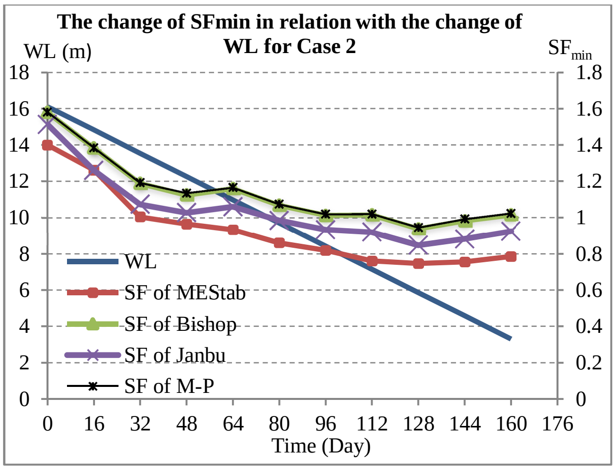

Fig.9. ***SF_{min}*** **calculated by MEStab and Slope-W for Case 2.** ***min[SF_{min}]=0.746***

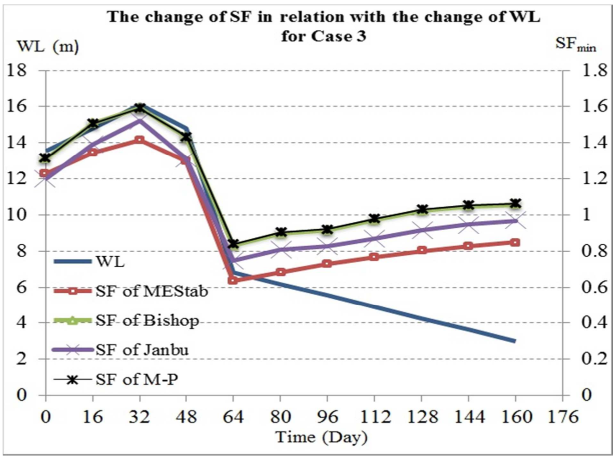

Fig.10. ***SF_{min}*** **calculated by MEStab and Slope-W for Case 3.** ***min[SF_{min}]=0.634***

We observe that the variation of the safety factor follows roughly this of the river level In cases 1 and 2, the minimum value of the safety factor occurs a few days before the end of the drop down of the river level. In case 3, the minimum safety factor occurs at the end of the rapid drop down of the river level. Then the SF_{min} grows up slightly despite the river level continues to drop; this is due to the delay in time of the ground water table after the rapid drop down of the river level. Besides, in all cases and time steps, the safety factors given by MEStab are smaller than those given by the other methods, which shows that the Fellenius method is the most conservative.

A parametric study of the influence of the soil permeability is now discussed for the three cases above of water level variation. Two values of the soil permeability are considered: $k_o=10^{-6}m/s$ and $k_o=10^{-7}m/s$. Figures 11 to 13 show the comparison of SF_{min} calculated by MEStab program with the two soil permeability values. We observe a similar trend of the safety factor evolution with time for both permeability values. But the minimum value reached after the water level drop is significantly smaller for the smaller soil permeability. Again, this is due to the delay of the groundwater table drop down with respect to the river level and to the consequent high pore water pressures remaining within the soil. As a practical consequence, these results prove the necessity of a good knowledge of the soil permeability from site measurements.

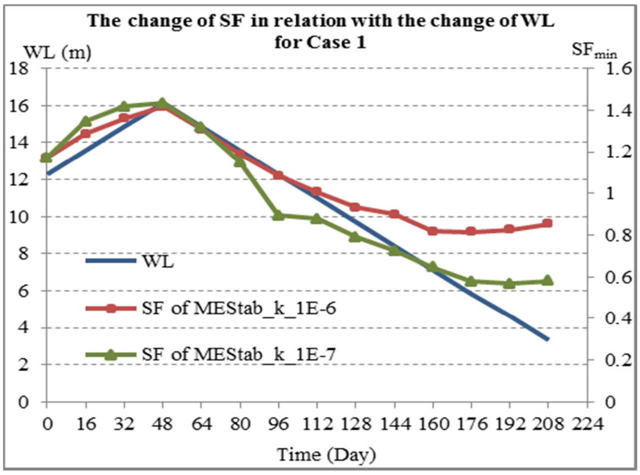

Fig.11. Influence of soil permeability on ***SF_{min}*** **, Case 1**

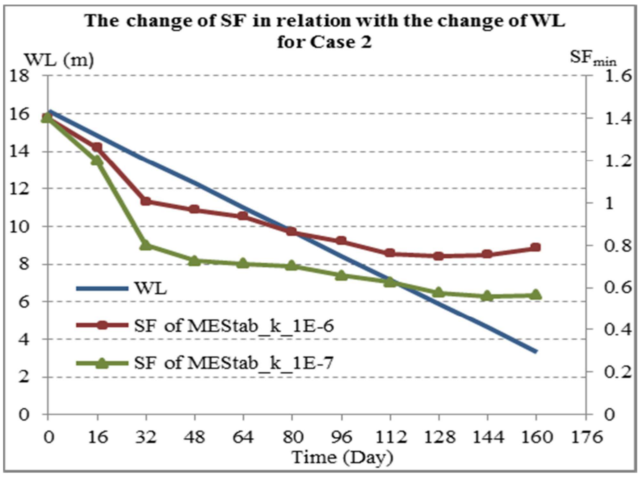

Fig.12. Influence of soil permeability on ***SF_{min}*** **, Case 2**

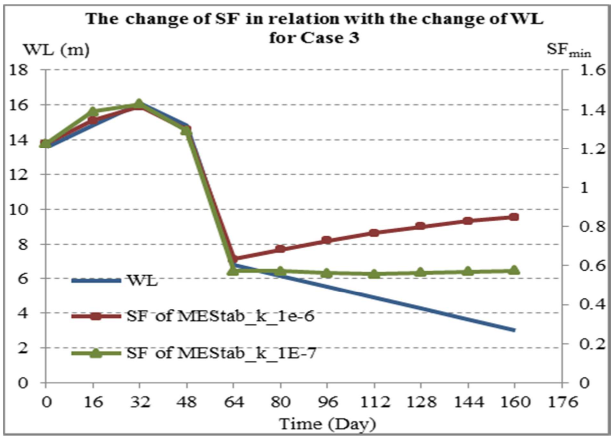

Fig. 13. Influence of soil permeability on SF_{min} , Case 3

4. DEFINITION OF A SAFETY ZONE ALONG THE RIVER BANK

Beside the value of the safety factor, another important parameter to be considered is the distance from bank's crest where the slip surface tends to emerge at the surface of the soil.

In Figure 14 we define X_0 as the distance from the bank crest to the top of the slip surface that produces the value of SF_{min} (called global SF_{min}). If we impose the slip surface to pass by another point X different from X_0, we obviously find that $SF_{min}(X) > SF_{min}(X_0)$. For each X value we can calculate the minimum safety factor $SF_{min}(X)$ among the set of slip surfaces emerging at distance X (called local SF_{min}). For illustration, we suppose a bank profile as shown in Figure 14 and its soil parameters as following: $C'=10kPa$; $\phi'=30°$; $\gamma=18kN/m^3$; $k_0=10^{-7}$ m/s; $n_o=0.45$.

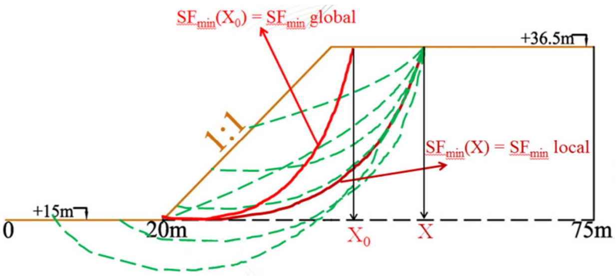

Fig.14. SF_{min} of a river bank

We calculate $SF_{min}(X)$ in function of the horizontal distance X. As the results of the calculations by different slice methods, Figure 15 shows that the value of SF_{min} increases with distance $X>X_0$. If the admissible value of the safety factor (SF_{adm}) is taken equal to 1.5 from some specification, we can find the distance X_{adm} corresponding to SF_{adm} and define a security zone $(X>X_{adm})$ and a hazard zone $(X<X_{adm})$ along the river bank from the plot.

The above zones depend on the water conditions as by the influence of WL variation, the curve of SF_{min} changes as shown in Figure 16. The initial WL and groundwater table are at the elevation of the crest (+36.5 m) then WL drops down with the rate of 0.08 m/day during 160 days. The SF_{min} curve moves down and leads the security zone move further to the right depending on the SF_{adm} value that we accept (SF_{adm}=1.5 for example).

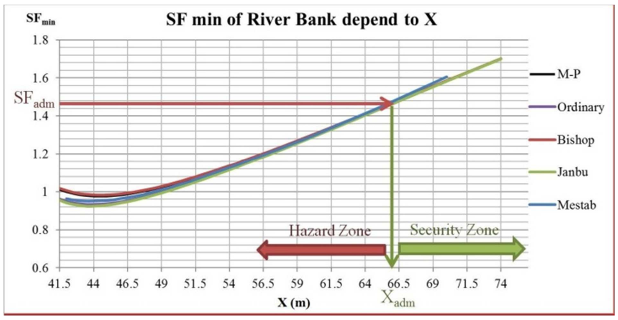

Fig.15. Definition of hazard and security zones

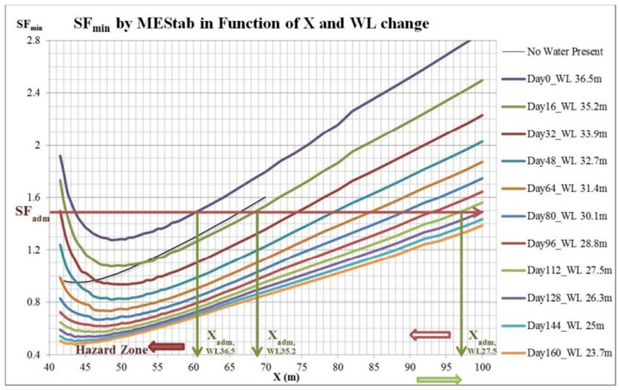

Fig. 16. Influence of WL variation on the extent of the Hazard zone

5. CONCLUSIONS

River bank instability is a major problem for both social and environmental aspects, especially in the case of high variations of the water level. Using simplified models coupling groundwater table variation and bank's slope stability with local hydrological data we demonstrate that the higher hazard of the river bank landslides occurs when the water level drops down. This is due to the delay of the dropping of the ground water table and thus to the remaining of high pore pressures in the soil. Therefore this hazard increases significantly if the ground water table in the immediate vicinity of the river bank is high or the dropping rate of the water level of the river is fast. Furthermore, the value of the soil permeability is also triggering the hazard of the river bank: the lower soil permeability the higher hazard of the river bank if the water level drops and vice-versa.

From the assumption of an admissible safety factor a risk zone has been defined at a distance X_{adm} from the bank crest. Inside this distance the value of SF is smaller than the admissible value SF_{adm} and the zone outside can be considered as a security zone because the SF_{min} are bigger than SF_{adm}. This original concept of defining a distance from the river bank separating hazard and security zones is of a great interest for risk management.

ACKNOWLEDGEMENTS

S. Ky author is highly grateful to Chrea Rada, professor at the Institute of Technology of Cambodia, for his help and for providing geotechnical data.

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