STRUCTURAL GEOLOGY IMPLICATIONS AS CRUCIAL FACTORS TO FACILITATE FORMING TYPHOON-TRIGGERED LANDSLIDES: CASE FROM HSIAOLIN VILLAGE DURING TYPHOON MORAKOT, 2009

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ABSTRACT: Typhoon Morakot had invaded and caused catastrophic hazard in southern Taiwan between 8th and 11th of August 2009. Exceeding rainfall threshold in many sides in mountainous areas triggered slope failure leading to widespread damage and loss of life. In our study we focused on one particular event, which was tragic in consequences. Hsiaolin Village located at the foothills of Shiendu Shan on the third day typhoon existence was entirely buried by massive landslide. We also utilize satellite images to analysis terrain deformations immediately during the event, collecting more information by extracting high resolution digital elevation model (DEM) and field working in study area, aim to figure out the relation between geologic conditions and landslides.

According to result, Two geological formations were involved in this incident- Tangenshan sandstone and Yenshuikeng shale. The boundary between those two formations propagated along the axis of the landslide. Wedge failure direction produced by bedding and fault surface system was almost parallel to the slope angle, which in some areas of the landslide could have happen even in dry conditions. Local uplift of the southern region of Hsiaolin village with assumed constant incision rate of the Chishan River seems to be quite noticeable. This assumption agrees with tilting of terraces, which we divided into three stages.

After measurements of tectonic situation of this area we came to a conclusion that structure geological setting played a major role as an indirect factor creating mechanism of the Hsiaolin landslide.

1. INTRODUCTION

Taiwan located at the western flank of the Pacific Ocean suffers from both climatic and geological processes causing numerous forms of natural disasters such as earthquakes, typhoons, floods, landslides or land subsidence

(Chang, 1996). Much greater damages are recorded in countryside areas, where multiplied effects of climatic and geologic processes trigger morphologic ones including: landslides, debris flaws, floods or land subsidence. Therefore, most of the phenomena as parallel factors often occur as a result one from the other. Annual statistics show that the island systematically experiences considerable damages caused by natural hazards. Many of them are fatal in consequences.

This study we devoted for a particular event, which took place in Hsiaolin village, southwestern Taiwan (Fig. 1a). On 9th of August 2009 at local time 6:16, cumulated load of rainfall triggered massive landslide burying entire village with all habitants. This catastrophic incident was caused by Typhoon Morakot, which invaded Taiwan between 8th and 11th of August 2009. Both approaches, field investigation and geomorphic study, helped us to build a model of evolution and geological structures above Hsiaolin. As a result we came put with a consistent opinion of strong influence of structure geological approach increasing the risk of natural disaster.

Typhoon Morakot was the most destructive storm to impact Taiwan in recorded history (CWB). It hit the island in the midnight of August 8th, 2009 on the sixth day after it formed about 1000 km to the east of Philippines. This widespread devastating incident left 701 people dead and 58 other missing and about $110 billion NTD ($3.3 billion USD) in damages (GEER-018; 2009). Rainfall level reached 2,777 mm, surpassing the previous record of 1,736 mm set by Typhoon Herb in 1996. This extreme amount of rain triggered numbers of landslides and caused flooding throughout southern Taiwan. According to Takahashi (2009) damage done by typhoon Morakot in Taiwan is mainly related to sediment disasters. Actually, the typhoon-triggered landslide buried entire Hsiaolin village killing nearly 500 people.

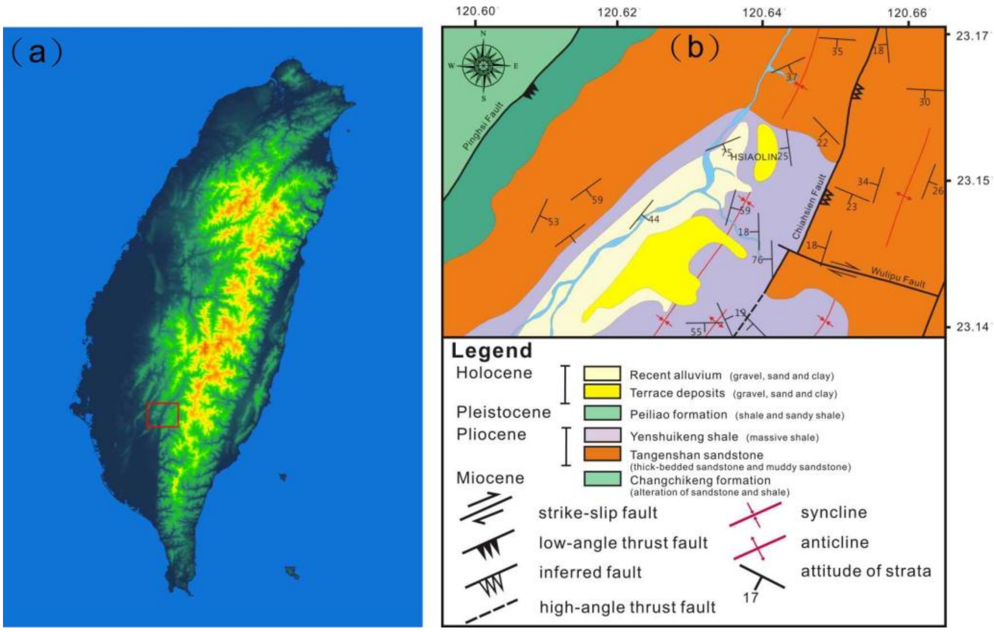

Fig. 1. (a) DEM of Taiwan island. Study area is located at the southwestern part of Western Foothills of Taiwan in Kaohsiung County, as shown by red rectangular frame. (b) The geological map of the Hsiaolin area (modified after Central Geological Survey). Hsiaolin village area is located at the boundary at the Tangenshan formation characterized by Miocene-Pliocene thick-bedded sandstone and Yenshuikeng formation represented by Pliocene massive shale.

2. REGIONAL SETTINGS

Hsiaolin village was located in Chiahsien Township, Kaohsiung County. By detailed observations of satellite images before the landslide of the hills over Hsiaolin village by 'Skyline Terra Explorer' provided by Center of Spaces and Remote Sensing Research, National Central University, we reckoned that the slopes were covered entirely by natural forest excluding foot of the slope were village itself was located.

Surrounding massifs are built by two formations which boundary propagates downhill almost parallel to the dip of the slope. Tangenshan formation is located at the northern study area characterized by Miocene-Pliocene thick-bedded sandstone and muddy sandstone (Figs. 1b and 2). In this formation there are distinguished three parts: (1) lower part sandstone, mostly composed by thick-bedded fine sandstone with interbedded medium-thin sandstone; (2) middle part sandstone, massive sandstone with strong bioturbated features; (3) upper part very fine sandstone with interbedded fine sandstone. Thick of very fine sandstone is between few centimeters to 2 meters. Bedding surfaces have been bioturbated with some signs of few hummocky cross-bedding.

Yenshuikeng formation is located in the southern part of the study area. It is built by Pliocene massive shale, strongly bioturbated, sometimes with interbedded thick or thin gray sandstone or muddy sandstone. This sandstone mostly has parallel bedding, occasionally ripple marks as well as cross-bedding. In Hsiaolin area we also distinguish Holocene sediments, which are formed into terraces and recent alluvium built by gravel, sand and clay deposits.

3. FIELD OBSERVATIONS

Our field investigation was mainly focused on structural setting around entire landslide area as well as its surroundings. The maximum high of the landslide crown reaches nearly 1300 meters above the sea level. The source area of the landslide laid from 700 m up to the landslide crown (Tsou et al., 2011). In addition, during our observations we found an evidence that on the surface of the source area before the landslide caused by typhoon Morakot already existed other debris, which likely where brought by previous event. It agrees with DEM observations of the area before the landslide, where in few spots we observed irregular and chaotic slope surface. Big boulders in higher parts on the head of the landslide (up to 10 m in diameter) were carried on the top of the surface and still after the incident were not transported down to the river level. Moreover, south of Hsiaolin village sets vast plain with an area about 1 km2, which also could be a part of one's landslide occurring in the past (Fig 3, the biggest area of the 1st stage terrace). Not well sorted, sharp and angular material with present tree trunks exclude debris flaw or river sediment processes in it.

Tectonic measurements brought the most explanatory evidence suggesting the landslide could be facilitated by geological factors. The strike of bedding of both, Tangenshan and Yenshuikeng formations trends in southwest direction (Figs. 2 and 3). Steep dip of bedding coincides with the slope what in a major part served as a surface rupture (Fig. 3d). On the other hand, the faulting system on the entire landslide area dips to northwest. Moreover, quite clear and relatively fresh pitch direction of lineations measured from the fault surfaces (Fig. 3e) is almost parallel the mass movement of the landslide. We assume that the landslide could be also eased by the same sense of motion. In such fitting circumstances, rainfall penetrating fault surfaces and bedding plains could trigger failure of the slope more efficiently.

Those two features create wedges which movement direction coinciding with the slope orientation what could lead to the wedge failure (Fig. 3). This wedge failure direction movement unfortunately was almost precise parallel to the dip and direction of the sliding debris where at the foothills of this setting was located Hsiaolin village. Few outcrops along and across the landslide confirmed our interpretation. We have also visited surrounding terrains taking measurements of neighboring valleys. As a result we came out with a conclusion that Tangenshan formation with Yenshuikeng formation at the boundary zone are under processes of the same faulting system.

Obviously it was not possible to confirm our satellite images study with the field observations concerning vegetation, constructions or any human agency factor, which could be involved as a landslide facilitating element. However as mentioned before, we rejected this concept to be one of principal component causing the landslide.

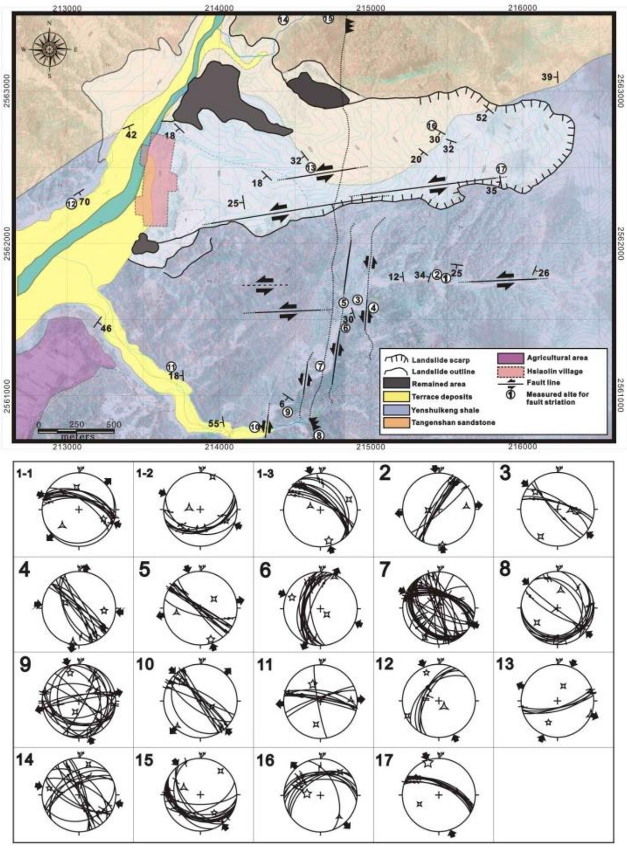

Fig. 2. Geological map of Hsiaolin landslide. Boundary between Tangenshan and Yenshuikeng formations run along the axis of the landslide. Bedding of both formations dip to south-west, which with faulting system striking in E-W generate wedge failure described in the text. Fault planes are shown as continuous lines and slickenside lineations are shown as small dots with arrows indicating the sense of motion (double arrows for strike-slip, outward directed arrows for normal slip, inward directed arrows for reverse slip). Inversion of fault slip data was performed according to the Angelier method (1989 and 1990). Axes of maximum compressive stress ($\sigma 1$), intermediate stress ($\sigma 2$) and minimum stress ($\sigma 3$) are 5, 4 and 3-branch stars, respectively. Large black arrows indicate trends of compression and/or extension.

4. DISCUSSION

The kinematics of the wedge failure was determined by combining tectonic setting with apparent angle of sliding friction ϕ. Apparent friction angle was estimated by several studies and it varies from 10° to 15° (Kuo, 2009; 林，2010; Tsou et al., 2011). For our study we chose Tsou et al. (2011) assumption $\phi = 14°$. As it is shown in Figure 3, we used bedding and fault surface as two sets of discontinuities. From the field observations we concluded that the landslide rupture surfaces where propagating on big scale combination of those two surfaces.

For the wedge failure, the direction of sliding rocks is controlled by direction of plunge drawn from an intersection of two discontinuities (Fig. 3c). Instability of the slope is brought by a steep angle of this plunge. In Hsiaolin case, the plunge direction fully agrees with the direction of natural slope. To overcome frictional resistance the plunge must exceed the sliding friction angle ϕ, what in our investigated landslide case had happened. That shows that the landslide could even initiate in dry conditions. As shown in Figure 3b daylight (slope) estimated at 20° and friction cone determines unstable zone where wedge failure becomes possible (reddish region).

Studying Skyline Terra Explorer before the incident excluded human activity involved as a principal factor for creating landslide pre-conditions. No deforestation or agriculture was carried out on the slopes above Hsiaolin village, hence no alteration of slope stability was influenced by weakening the soil steadiness. Also, no weighty constructions were set on the slopes, no undercutting or situated earth fills. Hsiaolin village itself along with a road following the Chishan valley was the only artificial structures located at the foot of the slopes. Consequently, no human factor was shaping landslide substructure, however still cannot be completely excluded from the list of factors influencing Hsiaolin landslide creation.

The landslide was initiated be heavy rainfall brought by typhoon Morakot. Rainwater infiltrating the soil caused slope failure on the third day after onside precipitation (Takahasi, 2009; Tsou et al., 2011). Because of that fact, soil of the Hsiaolin landslide slope could be classified as low-permeability soil in contrast to high-permeability soils where slope failure tends to happen prior to the occurrence of maximum rainfall intensity (Muntohar et al., 2009).

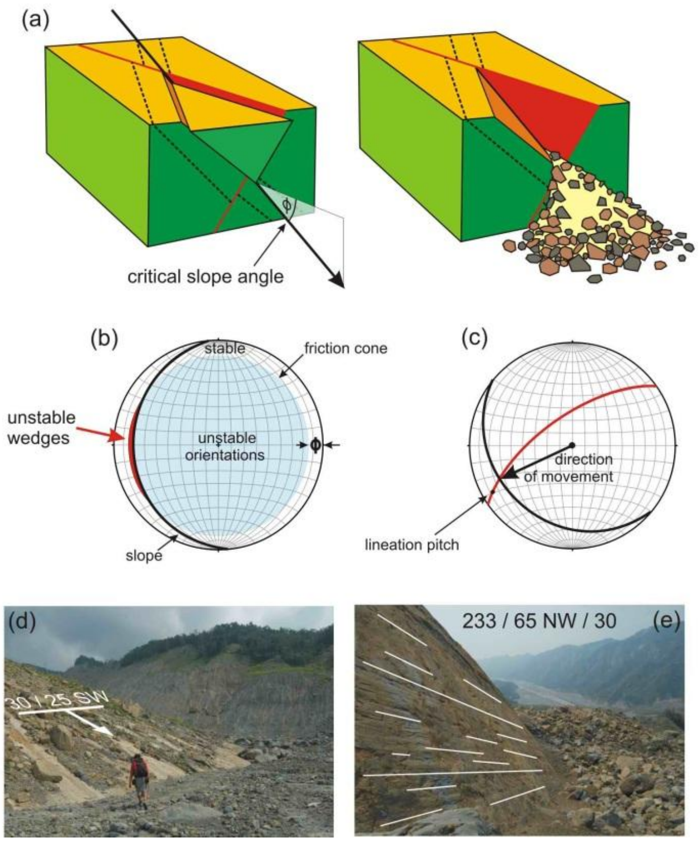

Fig. 3. (a) Wedge failure of the two discontinuities in Hsiaolin landslide. In this case faulting system combined with the bedding and formed an unstable wedge. (b) Unstable wedges estimated by slope friction angle ϕ, which in Hsiaolin area reaches 14° and slope angle striking almost N-S direction with a western dipping of 20°. (c) Direction of wedge failure movement determined by direction of the plunge of the line of the intersecting discontinuities. Lineation pitch fits well to the movement direction. (d) Photo of the bedding as a surface rapture also oriented downward to the valley. (e) Photo showing fault surface (looking down WSW direction) with clear, covering entire outcrop downdip lineations coinciding the mass movement.

5. CONCLUSION

Typhoon Morakot invading Taiwan exceeded rainfall threshold in numerous sides causing many landslide disasters bringing inestimable damages, not only in environment and loss of life, but also in people's memory. It is important to solve such phenomena for better understanding and future possible predictions. Our investigation on Hsiaolin landslide incident provides compelling evidence that structural geology situation played the major role in the landslide condition before it was triggered by typhoon Morakot. Expanded and the big scale wedge failure system powered the whole landslide mechanism (Fig. 4) along with local uplift of this area. This indirect factor was also strengthen by very active tectonic processes, likely unlocked, as we can observed throughout all Taiwan island. Combining field observations with geomorphic studies excluded human factor as a major component facilitating creating the landslide. However this issue cannot be omit when surveying any slope stability or risk concerning landslides prediction. Undoubtedly many factors should be concerned for such kind of investigations though always some will depend on subjective approach as its difficult or even impossible to compare hazard maps produced by different surveyors (Carrara, 1993). Also, studied areas depend on the importance of the region like a vehicle transit (Fujisawa K. et al., 2010) or expansion of public utilities, etc. It is still necessary to estimate occurrence time, establish relationship among the rainfall data, rainwater infiltration, slope hydraulic properties, and slope stability (Muntohar et al., 2009), but still geology and geomorphology are the basic factors controlling landslides in the long term (Chang et al., 2002).

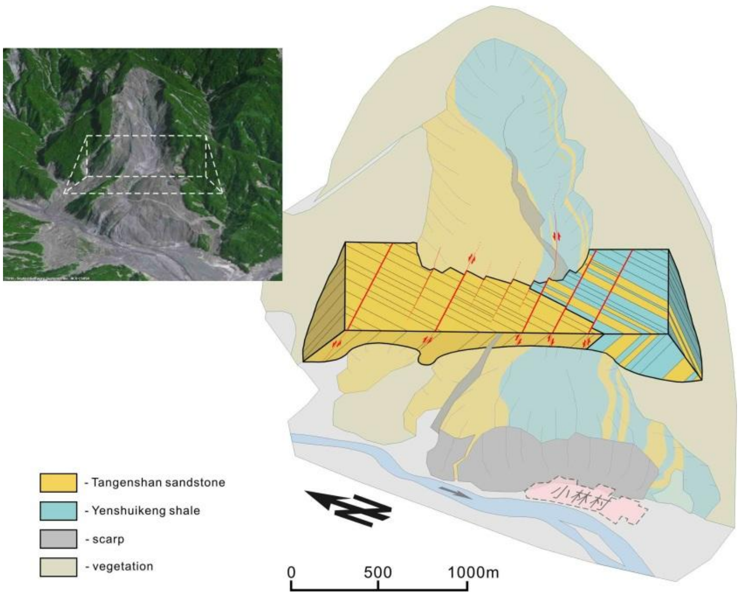

Fig. 4. Structural interpretation of the Hsiaolin landslide area. The boundary between Tangenshan and Yenshuikeng formations runs along the axis of the landslide. The bedding as well as faulting system creates v-shaped wedge failure which was a basic factor to contribute the landslide conditions. Satellite image of the landslide acquired by SkyLine Terra Explorer National Central University.

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REFERENCES

Broadband Array in Taiwan for Seismology (BATS) http://bats.earth.sinica.edu.tw/

Carrara A. (1993) Uncertainty in evaluationg landslide hazard and risk. Pred. and Percept. of Nat. Haz. 101-109.

Central Weather Bureau (CWB), http://www.cwb.gov.tw/
Chang, J.C., O. Slaymaker, (2002) Frequency and spatial distribution of landslides in a mountainous drainage basin: Western Foothills, Taiwan. Catena 46, 285-307.
Chang, J.C., (1996) Natural hazards in Taiwan. GeoJurnal 38.3, 251-257.
Chen, H.F., (1984) Crustal uplift and subsidence in Taiwan : an account based upon retriangulation results. Spec. Publ. of the Cent. Geol. Surv. 3, pp. 127–140.
Chen, H., S. Dadson, Y.G. Chi, (2006) Recent rainfall-induced landslides and debris flow in northern Taiwan. Geomorphology 77, 112-125.
Chen Y.G., T.K. Liu (2000) Holocene uplift and subsidence along an active tectonic margin southwestern Taiwan. Quat. Scien. Rev. 19, 923-930.
Fujisawa K., G. Marcat, Y. Nomura, A. Pasuto (2010) Management of typhoon-induced landslide in Otomura (Japan). Geomorphology 124, 150-156.
Geoengineering Extreme Events Reconnaissance (GEER) (2009) Reconnaissance report of the August 8, 2009 Typhoon Morakot. Taiwan Report of the National Science Foundation-Sponsored Team.
Hsieh M.L., P.M. Liew, M.Y. Hsu (2004) Holocene tectonic uplift on the Hua-tung coast, eastern Taiwan. Quatern. Intern. 115-116, 47-70.
Hung J.J., (2000) Chi-Chi Earthquake induced landslides in Taiwan. Earthq. Eng. and Eng. Seism., Vol. 2, Nr 2, 25-33.
Kuo C.Y. (2009) Modeling of debris flow. Seminar National Centraul University, Taiwan.
Liew P.M., P.A. Pirazzoli, M.L. Hsieh, M. Arnold, J.P. Barusseau, M. Fontugne, P. Giresse (1993) Holocene tectonic uplift deducted from elevated shorelines, eastern Coastal Range of Taiwan. Tectonophysics, 222, 55-68.
Montgomery D.R., W.E. Dietrich (1994) A physically based model for the topographic control on shallow landsliding. Water Reso. Rsearch, Vol. 30, NO. 4, 1153-1171.
Muntohar A.S., H.J. Liao (2009) Analysis of rainfall-induced infinite slope failure during typhoon using a hydrological-geotechnical model. Environ. Geol., 56,1145-1159.
Schuster R. L., L. M. Highland (2006) The third Hans Cloos lecture. Urban landslides: socioeconomic impacts and overview of mitigative strategies. Bull Eng Geol Environ (2007), 66, 1-27.
Stolar D. B., S. D. Willet, D. R. Montgomery (2007) Characterization of topographic steady state in Taiwan. Earth Planet. Sci. Lett., 261, 421-431.
Takahashi, T. (2009) Typhoon disaster in Taiwan in August 2009. Report of Dia Consultants Co.
Tsou, C.Y., Z.Y. Feng, M. Chigara (2011) Catastrophic landslide induced by Typhoon Morakot, Shiaolin, Taiwan. Geomorphology, 127, 166-178.
USGS, Landslide types and processes. http://pubs.usgs.gov/fs/2004/3072/
Wang C.H., W.C. Burnett (1990) Holocene mean uplift rates across an active plate-collision boundary in Taiwan. Sience, Vol. 248 no. 4952 pp. 204-206.
Yu S.B., H.Y. Chen, L.C. Kuo (1997) Velocity field of GPS stations in the Taiwan area. Tectonophysics, 274, 41-59.
林錫宏(2010) 大規模岩坡的山崩潛勢判釋與危險度評估。經濟部 99 年度臺加技術合作訓練計畫，研習報告。