Landslides in Hong Kong under the influence of climate change

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ABSTRACT

The effect of climate change has created an acute challenge on various aspects of our lives. On the aspect of slope safety, the Geotechnical Engineering Office in Hong Kong has been studying the impact of climate change on landslides in Hong Kong with a view to gearing up the Slope Safety System as well as enhancing system and community resilience towards the challenge. This paper gives an overview on the appraisal of the potential impact of climate change on landslides in the local context given the projected climate. In this regard, the key meteorological and environmental factors that have roles to play on landslides, including rainfall and other secondary factors such as evapotranspiration and vegetation, have been considered. The potential variation of these factors under the changing climate and the corresponding impact on landslides have been evaluated. More frequent and severe extreme rainfall events could result in landslides of unprecedented number, scale and mobility. The secondary factors would mainly alter the slope surface characteristics and groundwater regime, which generally lead to a higher vulnerability to landslides. The appraisal provides valuable information to decision-holders in paving the way for managing the challenge from slope safety perspective.

Keywords: landslide; climate change

1 INTRODUCTION

With a view to stepping up the preparedness of slope safety for the sake of public safety, the Geotechnical Engineering Office (GEO) has been studying the impact of climate change on landslides in Hong Kong. In this connection, the climate change influence on the key meteorological and environmental factors that have roles to play on landslides, including rainfall and other factors such as evapotranspiration and vegetation, has been identified for a comprehensive assessment. This paper gives an overview on the findings of the assessment which shed light on the importance of gearing up the city to manage the slope safety challenge ahead.

2 INFLUENCE OF CLIMATE CHANGE ON LANDSLIDES

Seven landslide-affecting meteorological or environmental factors (referred to as 'factors' hereafter) being susceptible to the influence of climate change and relevant to Hong Kong have been identified. These include

(i) rainfall,
(ii) evapotranspiration,
(iii) vegetation,
(iv) sea level,
(v) high wind,
(vi) hillfire, and
(vii) drought.

Considering that landslides in Hong Kong are primarily rain-induced, rainfall is taken as a 'primary factor' and the other six factors are collectively referred to as 'secondary factors' in the present context.

Attempts have been made to obtain the projections of these factors under climate change via various channels including literature review and consultation with the Hong Kong Observatory (HKO) and some experts of the relevant fields. In case projections are not available, the key governing meteorological variables have been mapped out and their respective projections have been collated to shed some light on the potential changes of the factors in future. In view that climate projections are fraught with uncertainties (e.g. limitations of climate modelling and divergent predictions from different models) and dependent of the different scenarios of greenhouse gases concentration (viz. four sets of Representative Concentration Pathway (RCP) adopted in IPCC (2013)), only the qualitative terms of the projections are presented in this paper. Using the information, a qualitative assessment has been made to reveal the effects on landslides in Hong Kong and the assessment findings pertaining to each of the seven factors are presented in this section.

2.1 Rainfall

The correlation between rainfall and landslides has been well established. Among the various aspects of rainfall, extreme rainfall events are of great concern

from slope safety point of view where these could result in widespread and serious landslides. Under the influence of climate change, meteorologists are of the view that, apart from an increase in annual rainfall, there would be an escalation of the frequency and severity of the extreme rainfall events in Hong Kong (HKO 2015). In fact, there are indications that the short-duration rainfall in Hong Kong has already been significantly affected, e.g. the maximum hourly rainfall record since 1885 has been broken several times after 1966 with the time intervals between new records getting shorter (Fig. 1).

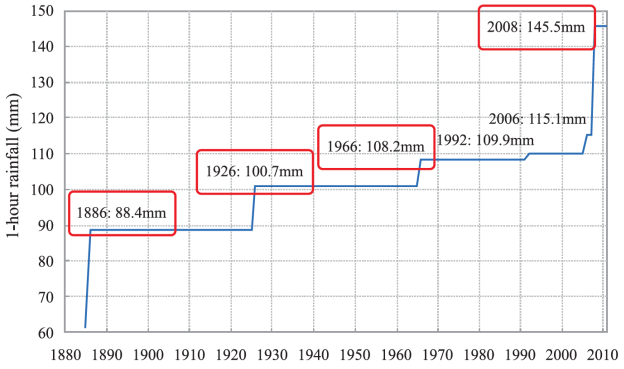

Fig. 1. Record-breaking one hour rainfall recorded by the principal raingauge in HKO, Tsim Sha Tsui (Source: HKO).

The landslide challenge could be unprecedented along with the more frequent and severe extreme rainfall events. The frequency and scale of man-made slope failures could increase. Washout failures could become more frequent and serious due to the exacerbation of concentrated flow of surface water given the increased short-duration rainfall intensity. Widespread natural terrain landslides and debris flows could occur, with escalated frequency, scale and mobility. For example, Lantau Island was severely hit by an exceptionally intense rainstorm in June 2008 triggering over 2,400 natural terrain landslides (Fig. 2). Many of the landslides were sizeable with a much longer runout than those that have previously occurred in Hong Kong. The landslides resulted in significant social disruption including the blockage of several key roads that provide the sole access to remote rural communities and evacuation of over 25 houses.

2.2 Evapotranspiration

As part of the water cycle, evapotranspiration is one of the factors governing the amount of water in the ground. Li et al. (2016) presented projections of evapotranspiration across China including Hong Kong under the upper- and lower-bound greenhouse gases concentration scenarios. From the projections, evapotranspiration in Hong Kong is anticipated to increase or exhibit negligible change.

Fig. 2. Clusters of landslides at Tai O, Lantau triggered by the rainstorm in June 2008

An increase in evapotranspiration theoretically maintains a higher soil matric suction and provides additional margin against the build-up of pore water pressure at shallow soil depth, which points to a reduction in the potential of shallow landslides on slopes. However, such apparent beneficial effect could vanish rapidly under mild to intense rainfall particularly for granular soil being common in the superficial layer of slope-forming materials in Hong Kong as a result rendering insignificant contribution to slope stability. This is evidenced by a local study pertaining to field monitoring of the change in soil matric suction for which suction was destroyed rapidly, in several hours, under rainfall with intensity higher than 20 mm/hr in wet seasons (Leung et al. 2011; Leung & Ng 2013).

2.3 Vegetation

Vegetation plays a role in determining the surface characteristics of slopes and water balance. Vegetation growth involves very complex interactions of environmental, climatic and biophysical variables. Vegetation at different elevations and topography may comprise different and wide ranges of species which could exhibit a varying degree of responses under the changing climate. Within a habitat, some species may lose fitness and hence reduce in abundance and distribution, whilst there would be upward migration of tropical species to higher altitudes. It is therefore highly difficult to project the trend of vegetation growth from species- or habitat-specific perspective, and limited researches have been conducted on the subject in Hong Kong.

Whilst acknowledging the aforesaid limitations, an attempt has been made to identify factor which may shed some light on the overall trend of vegetation growth under climate change for the context of assessment of the associated landslide impact. In this respect, vegetation phenology, which refers to the timing of annually recurrent reproductive biological events such as flowering, breeding and migration (generally speaking the growing season), may provide some indications. According to the regional phenology-related researches and studies conducted

worldwide (Piao et al. 2006; Wang et al. 2017), global warming which in general drives the biological process probably advances the start and delays the end of growing season of vegetation leading to prolonged growing periods. Aligning with the global warming trend, vegetation growth in Hong Kong may be promoted in broad sense alongside with the promoted phenology, although any trend in reality is yet to be supported by detailed study together with a consideration of other factors that may govern the phenology development.

Based on the deduced hypothetical trend of promoted vegetation growth under climate change, the implications on landslide have been assessed. It is anticipated that the potential of surface erosion and shallow landslides on slopes may be reduced given the beneficial effects contributed by vegetation (Greenwood et al. 2004; Forbes & Broadhead 2011; Tang et al. 2018), viz. (i) reinforcement of soil by root anchorage, (ii) reduction of soil moisture by root water uptake, and (iii) protection of slope surface by shielding against direct rainfall and slowing down surface runoff. The effects are generally confined to shallow depth around the root zones whilst the potential of deep-seated landslides may not be significantly affected. On the other hand, promoted vegetation growth could also bring about adverse effects on slope stability. Local experience shows that the growth of roots could penetrate into rock joint apertures and wedging the joints open rendering a higher potential of boulder/rock falls (Fig. 3) or structural control landslides. Recently, a sizeable landslide on a rock slope exposed the penetration of tree roots to a considerable depth within the jointed rock mass (Fig. 4). The slope deterioration aggravated by root-wedging action coupling with some other factors had contributed to the sizeable landslide.

Fig. 3. Rockfall contributed by root-wedging action.

Fig. 4. Sizeable rockslide exposing the penetration of tree roots to a considerable depth within the jointed rock mass.

2.4 Sea Level

Variation of sea level could have a bearing on groundwater regime. Under the changing climate, ocean expands as it warms. This, together with glacier melting to some extent, has contributed to the global rise in sea level. Hong Kong is aligning with the same trend with the rise in sea level (HKO 2015).

The rise in sea level would have a two-fold impact on slope stability, viz. the elevation of groundwater table and the aggravation of coastal slope erosion by enhanced wave action. The elevation of groundwater table could reduce the stability margin of near-shore slopes. On the other hand, toe erosion of coastal slopes could be aggravated as the progressively rising sea level brings wave action to higher levels and permits larger waves to reach the slopes through deepening of near-shore water (Bird 1996). The larger waves also promote more severe turbulence exacerbating the extent of erosion. With the loss of toe mass, the overall slope stability may in turn be adversely affected rendering landslide impact to extend to the uphill areas (Fig. 5). In addition, an increasing trend is predicted for the magnitude of storm surges in Hong Kong (Lee et al. 2010). This effect, despite being transient, coupling with the projected sea level rise associated with climate change could further exacerbate the impacts.

2.5 High Wind

At times, the force of wind on trees can be significant rendering tree fall and load transmission to slopes particularly under tropical cyclones. Under the changing climate, the warmer sea surface would provide additional heat energy to intensify tropical cyclones. According to IPCC (2013), there is a global increasing trend of wind speed generated by tropical cyclones. Hong Kong is expected to follow the same trend and this in effect suggests stronger high wind.

Fig. 5. Coastal slope possibly experienced an upward extension of failure following the loss of toe mass due to erosion.

The stronger high wind would render slopes more vulnerable to landsliding including rock/boulder falls. High wind may cause uprooting of trees and root levering resulting in exposure of bare slope surface (Fig. 6) and loosening of the shallow groundmass that favour rainfall infiltration (e.g. Forbes & Broadhead 2011; Gariano & Guzzetti 2016). It could also exacerbate the root-wedging action on rock joints destabilizing metastable rock blocks and boulders. Moreover, high wind could induce drag force on slopes via trees further increasing the potential of local instability.

Fig. 6. Tree fall exposing bare soil on a steep slope.

2.6 Hillfire

The surface characteristics of slopes could be altered by hillfire. Although there is a lack of studies on the influence of climate change on hillfire in Hong Kong, the projections of some meteorological variables shed light on its vulnerability under the changing climate. Local historical data established a strong correlation between fire outbreaks and relative humidity in that a higher number of fire outbreaks occurred during periods of relatively lower humidity level. According to the projections given in IPCC (2013), the relative humidity of Hong Kong would slightly decrease under climate change. Combined with the temperature rise along with global warming, slopes in Hong Kong could be more vulnerable to hillfire.

The potential increase in the vulnerability to hillfire could bring about an adverse effect on slope stability. Hillfire damages plant canopy and vegetation which in effect destroys the surface protection of slopes (Fig. 7) where beneficial factors against the occurrence of landslides, such as the interception of rainfall and lowering of the speed of surface runoff, would be vanished. In this connection, slopes become more susceptible to surface erosion before the re-establishment of vegetation. On the other hand, hillfire could alter the hydrological response of the affected catchments. It causes water repellency in soil that could result in reduced infiltration, increased surface runoff and more erodible soil which may in turn promote debris flow initiation (Zheng & Lourenço 2018). Post-hillfire debris flows have been reported to occur globally, e.g. United States, Australia and Mediterranean countries. The alteration of hydrological response of a watershed can render much less rainfall to trigger debris flows from burned basins, e.g. rainfall as little as 7 mm/hr has triggered debris flows in southern California, than from unburned areas and this could be of concern given the little warning.

Fig. 7. Hillfire damage increasing the susceptibility to erosion.

2.7 Drought

Whilst drought reduces soil moisture and increases soil matric suction, it could wilt vegetation and weaken root reinforcement effect on slope stability as a result of root degradation or dieback (Forbes & Broadhead 2011). The increased soil matric suction may in turn increase the magnitude of repeated wetting and drying cycles. For slopes comprising clayey soil, the soil may exhibit shrinkage cracks. The weakening of root reinforcement together with the possible exacerbation

of slope deterioration under the amplified wetting and drying cycles and shrinkage cracks development could render slopes more vulnerable to landsliding if followed by rainfall. Wang et al. (2018) presented projections of drought in the Pearl River Basin. The frequency, duration and severity of the future drought events in the Pearl River Delta would generally exhibit no significant variation under climate change, particularly for the coastal cities including Hong Kong. Given the lack of a prominent trend, drought would have little impact in varying the degree of landslide risk in Hong Kong.

3 DISCUSSION

Findings from the qualitative assessment suggest that the more frequent and severe extreme rainfall events (i.e. the primary factor) along with climate change would result in a direct landslide impact where landslides could be of unprecedented number, scale and mobility. In respect of the secondary factors, they would alter mainly the slope surface characteristics and groundwater regime, generally leading to a higher vulnerability to landslides. As regard the extent of landslide impact, the magnitude of projected changes of the secondary factors are relatively insignificant in the context of landslide and the changes are generally expected to take place in a progressive manner which may not necessarily result in a notable impact on landslides. Comparing with that of the primary factor, the impact associated with the secondary factors should be much less significant and to some extent this may be enveloped by the impact arising from extreme rainfall events. All in all, it is prudent that the more frequent and severe extreme rainfall events would pose a particular challenge on the slope safety in Hong Kong.

The GEO has been adopting a systematic approach in managing the potential challenge ahead particularly towards extreme landslide events. In this respect, a number of studies have been conducted over the past decade (Ho et al. 2017) which include taking stock of relevant climate change studies, identifying the nature and scale of credible extreme landslide events, assessing the severity of landslide consequences, carrying out 'stress test' of the landslide emergency management system using scenario-based assessments, etc.

Based on the studies, the GEO has put forward expanded efforts to enhance the slope safety preparedness in Hong Kong. The impact has been considered from a strategy, policy and technical perspective for development of the necessary risk management actions. Some notable examples include the systematic implementation of mitigation measures on deserving slopes and catchments, enhancing and streamlining the landslide emergency services, enhancing the landslide warning system, improving coordination of Government emergency services with emphasis on the possible compounding effects arising from concurrent multiple hazards (e.g. landslides, flooding and storm surges), etc. Apart from system resilience, community resilience to landslides under extreme rainfall conditions would also be enhanced. It is imperative that the community maintains highly vigilant about serious landslides and be better prepared to deal with extreme rainfall events, acknowledging that it is neither practical nor cost-effective to rely solely on engineering solutions to manage the risk.

4 CONCLUSION

Climate change is liable to induce variations in the meteorological as well as environmental conditions, bearing both direct and indirect implications on landslides to different extents. The qualitative assessment made on the seven identified landslide-affecting factors, viz. rainfall, evapotranspiration, vegetation, sea level, high wind, hillfire and drought, has revealed the potential impact of climate change on landslides in Hong Kong. In essence, the more frequent and severe extreme rainfall events could result in landslides of unprecedented number, scale and mobility for the geological conditions in Hong Kong. As for the above secondary factors, they would alter mainly the slope surface characteristics and groundwater regime, generally leading to a higher vulnerability to landslides. The understanding supports the various initiatives in place to enhance both system and community resilience that gears up the city in managing the slope safety challenges ahead taking due account of the influence of climate change.

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REFERENCES

Bird, E.C.F. (1996). Coastal erosion and rising sea-level. In: J.D. Milliman and B.U. Haq (eds) Sea-Level Rise and Coastal Subsidence. Springer. 369pp.

Forbes, K. and Broadhead, J. (2011). Forests and landslides - The role of trees and forests in the prevention of landslides and rehabilitation of landslide-affected areas in Asia. FAO RAP Publication 2011/19. 42pp.

Gariano, S.L. and Guzzetti, F. (2016). Landslides in a changing climate. Earth-Science Reviews, Vol. 162, 227-252.

Greenwood, J.R., Norris, J.E. and Wint, J. (2004). Assessing the contribution of vegetation to slope stability. Proceedings of the Institution of Civil Engineers - Geotechnical Engineering, Vol. 157, 199-207.

HKO (2015). Hong Kong in a Warming World. Climate Change Pamphlet by the Hong Kong Observatory, Hong Kong, 29pp.

Ho, K.K.S., Sun, H.W., Wong, A.C.W. and Yam, C.F. (2017). Enhancing slope stability preparedness for extreme rainfall and potential climate change impacts in Hong Kong. In: Ho,

K.K.S. et. al. (eds), Slope Safety Preparedness for Impact of Climate Change, CRC Press. 572pp.

IPCC (2013). Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. [T.F. Stocker, D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, USA. 1535pp.

Lee, B.Y., Wong, W.T. and Woo, W.C. (2010). Sea-level rise and storm surge - impacts of climate change on Hong Kong. HKIE Civil Division Conference 2010. 12-14 April, 2010.

Leung, A.K. and Ng, C.W. W. (2013). Seasonal movement and groundwater flow mechanism in an unsaturated saprolitic hillslope. Landslides, Vol. 10(4), 455-467.

Leung, A.K., Sun, H.W., Millis, S.W., Pappin, J.W., Ng, C.W.W. and Wong, H.N. (2011). Field monitoring of an unsaturated saprolitic hillslope. Canadian Geotechnical Journal, Vol. 48, 339-353.

Li, J., Chen, Y. D., Zhang, L., Zhang, Q. and Chiew, F.H.S. (2016). Future changes in floods and water availability across China: linkage with changing climate and uncertainties. Journal of Hydrometeorology, Vol. 14(7), 1295-1314.

Piao, S., Fang, J., Zhou, L., Ciais, P. and Zhu, B. (2006). Variations in satellite-derived phenology in China's temperate vegetation. Global Change Biology, Vol. 12, 672-685.

Tang, A.M. et al. (2018). Atmosphere-vegetation-soil interactions in a climate change context; impact of changing conditions on engineered transport infrastructure slopes in Europe. Quarterly Journal of Engineering Geology and Hydrogeology, Vol. 51(2), 156-168. Wang, X., Gao, Q., Wang, C., Yu, M. (2017). Spatiotemporal patterns of vegetation phenology change and relationships with climate in the two transects of East China. Global Ecology and Conservation, Vol. 10, 206-219.

Wang, Z., Zhong, R., Lai, L., Zeng, Z., Lian, Y. and Bai, X. (2018). Climate change enhances the severity and variability of drought in the Pearl River Basin in South China in the 21st century. Agricultural and Forest Meteorology, Vol. 249, 149-162.

Zheng, S. and Lourenço, S.D.N. (2018). Post-wildfire debris flows in Greater China. 2nd JTC1 Workshop on Triggering and Propagation of Rapid Flow-like Landslides, Hong Kong.