Study of 24-hour probable maximum precipitation and associated landslide hazards for Hong Kong

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ABSTRACT

Probable Maximum Precipitation (PMP), which is an extreme rainfall level widely used for dam and reservoir engineering, has been taken as a practical reference for expressing extreme rainfall events for formulating landslide scenarios in Hong Kong’s landslide emergency preparedness. Landslide hazards had been assessed based on scenarios corresponding to 90% of the 24-hour PMP, which was estimated by Hong Kong Observatory in 1999. The results indicated that more than 3,000 landslides affecting buildings or roads would occur if Hong Kong Island is struck by a storm of this level of rainfall. An updating of the 24-hour PMP has recently been carried out using the method of storm transposition. In this method, the major storm associated with Typhoon Morakot, which lashed Taiwan seriously in 2009, was targeted to be transposed to Hong Kong. Based on the Step Duration Orographic Intensification Factor (SDOIF) Method, storm separation technique was applied to separate the convergence component from the orographic component of the major storm and the convergence component was transposed and then combined with the local orographic factors in Hong Kong for PMP estimate. This paper will present the method adopted in the transposition and discuss the results for the updating of the PMP estimate. The assessment of the landslide scenarios corresponding to the updated PMP will also be discussed.

Keywords: probable maximum precipitation, landslides, emergency preparedness

1 INTRODUCTION

The Probable Maximum Precipitation (PMP) for Hong Kong was firstly derived in 1968 for waterworks developments by the Hong Kong Observatory (HKO) (Bell & Chin 1968). In 1998, the Geotechnical Engineering Office (GEO) and the HKO collaborated on a study to update the 24-hour PMP using the moisture maximization approach (denoted as 1999 PMP) (HKO, 1999). As per the results of the study, the 24-hour PMP was estimated to be 1,250 mm for an area of 10 km². The 1999 PMP was used as a benchmark rainfall for assessment of possible extreme landslide scenarios in GEO’s review of emergency preparedness (Sun et al, 2001). During the period from 2011 to 2014, a 24-hour PMP updating study was undertaken using the international best practice.

2 UPDATING OF 24-HOUR PMP

2.1 Storm Survey

In the latest PMP study, a rainstorm survey covering various meteorologically similar areas in the region, including Hong Kong, Taiwan, Guangdong, Guangxi, Hainan, Fujian and Zhejiang, was conducted. Following a detailed review of the severity of the storms and data availability and quality, four major rainstorms in Taiwan (viz. Typhoon Herb in 1996, Typhoon Aere in 2004, Typhoon Haitang in 2005 and Typhoon Morakot in 2009) were selected for transposition analysis using the storm separation technique (viz. the Step Duration Orographic Intensification Factors (SDOIF) Method).

2.2 Storm Transposition & Moisture Maximization

The procedures of the SDOIF method are illustrated in Fig. 1. The rainfall for each selected rainstorm was decomposed into two components (i.e. convergence component and orographic component respectively) to facilitate the transposition analysis. A statistical approach combined with synoptic analysis and topographic features was adopted to estimate the orographic factors (i.e. SDOIF) for Taiwan for separation of the convergence components from the total rainfalls. By examining the geographical variation of the mean historical annual maximum rainfall at each
raingauge normalized with the mean historical annual maximum rainfall at base raingauge stations, the SDOIF were estimated (WMO, 2009). The locations of the base stations were selected at areas without orographic influence and corresponding to the direction of the southwest prevailing moisture flux to Taiwan during the representative storm.

By accounting for the SDOIF of Taiwan (to eliminate the orographic effect), the isohyets corresponding to the convergence components of the above four rainstorms were derived. Then, from the viewpoints of design storm in engineering hydrology, the convergence components of these rainstorms were further generalized to elliptical-shaped isohyets with an aspect ratio of 1.6 to establish the so-called 'generalized convergence component' (See Fig. 2).

On the other hand, the local SDOIF for Hong Kong were also developed in a similar manner with data from base stations corresponding to northeastern/northern prevailing moisture flux.

For the purpose of combining the generalized convergence component with the SDOIF, Hong Kong was divided into a grid of 12 by 10 cells. The centre of the generalized convergence component was superimposed to the location of the peak value of the SDOIF for Hong Kong (near Tai Mo Shan). The generalized convergence component was then multiplied by the SDOIF for Hong Kong at the corresponding locations at each grid cell to take into account the local orographic effect. The outcome is called embryonic PMP.

The superimposition of the generalized convergence component with the SDOIF for Hong Kong was repeated for various orientations of the generalized convergence component in order to ascertain the critical combination. The orientation refers to the bearing of the major axis of the isohyets of the generalized convergence component. The critical embryonic PMP was further adjusted by a moisture maximization ratio to derive the PMP estimate.

The moisture maximization ratio is the ratio of the maximum precipitable water ($W_2$) in the design location (i.e. Hong Kong) to the precipitable water ($W_1$) for the representative storm (i.e. Typhoon Morakot). Precipitable water is the total atmospheric water vapour contained in a vertical column of unit cross sectional area extending between any two specified levels and is correlated to dew point under the assumption of saturated pseudo-adiabatic atmosphere. $W_2$ corresponds to the maximum persisting 12-hour dew point of 100-year return period in Hong Kong which was deduced from the observations at the HKO between 1961 and 2013. $W_1$ corresponds to the representative persisting 12-hour dew point in Taiwan which was estimated from the observations at four stations in Taiwan during passage of Typhoon Morakot over the island.

In addition to the peak value of the SDOIF at Tai Mo Shan (near central part of Hong Kong), there is another local peak located at Lantau (western part of Hong Kong). Hence, the above procedure was repeated by superimposing the centre of the generalized convergent component to the peak of SDOIF at Lantau.

2.3 Updated PMP

The isohyets of the 24-hour PMP centred at Tai Mo Shan and Lantau are shown in Fig. 3 and 4 respectively. Their Depth-Area-Duration (DAD) curves are shown in
**Fig. 5.** The two curves are very similar. It is recommended that for the purpose of assessing landslides responses, the average of the two DAD curves as shown in Fig. 5 should be adopted. For an area of 10 km$^2$, the 24-hour PMP was estimated to be 1,510 mm.

Elliptical-shaped isohyets derived from the average DAD curve with an aspect ratio of 1.6 were then established (See Table 1).

**Table 1.** Isohyets of the updated 24-hour PMP for assessing landslide responses

| Isohyet (mm) | Minor Axis (km) | Major Axis (km) | Area (km$^2$) |
|-------------|----------------|----------------|--------------|
| 1,500       | 2.1            | 3.4            | 5.8          |
| 1,400       | 4.0            | 6.4            | 20           |
| 1,300       | 7.5            | 11.9           | 70           |
| 1,200       | 10.9           | 17.5           | 150          |
| 1,100       | 17.8           | 28.5           | 400          |
| 1,000       | 22.4           | 35.8           | 630          |
| 900         | 28.2           | 45.1           | 1,000        |
| 800         | 35.7           | 57.1           | 1,600        |
| 700         | 40.9           | 65.4           | 2,100        |
| 600         | 44.2           | 70.6           | 2,450        |
| 500         | 47.2           | 75.5           | 2,800        |

Note: Area of ellipse = $\pi \times (\text{major axis} \times \text{minor axis}) / 4$

**2.4 Evaluation of PMP**

To examine its rationality and reliability, the updated 24-hour PMP was compared with the extreme rainfall records of Hong Kong, the Southeast China region including Zhejiang, Fujian, Guangdong, Guangxi, Hainan and Taiwan, and other parts of the world (See Fig. 6) (Kung, 2010; Wang, 1999 & Wang, 2002). It was also compared to the PMP estimates for some existing hydropower projects in China (See Fig. 7) (MWR, 1995; Wang, 1999 & Wang, 2002).

![Fig. 6. Comparison of updated Hong Kong 24-hour PMP with extreme rainfall records in Hong Kong, Southeast China including Taiwan as well as the world records](image)

To summarise, the updated Hong Kong 24-hour PMP is higher than the extreme rainfall records in Hong Kong to some noticeable extent. It is also higher than the rainfall records in Zhejiang, Fujian, Guangdong, Guangxi and Hainan. It is approaching to the records in Taiwan. It is lower than the world records by about

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**Note:** The rainfall above refers to the average rainfall over the corresponding area.
17% only. On the other hand, it does not exceed the enveloping line of the relations between 24-hour PMP estimates and the size of catchment areas for the existing hydropower projects in China (see Fig. 7).

The updated Hong Kong 24-hour PMP is considered reasonable. With rainfall records for 130 years at the HKO, the 24-hour rainfall of notional return period of 10,000 years was estimated to be about 1,050 mm. This amount of rainfall is equivalent to about 70% of the updated PMP. This indicates that such an event is possible.

The numbers of landslides on natural terrain and man-made slopes have been estimated. The assumptions of the assessments are summarised in Sections 3.2 and 3.3 below:

### 3.2 Natural Terrain Landslide Models

The number of natural terrain landslides was estimated from a landslide frequency model. The landslide frequency model was derived from extrapolation of rainfall-landslide correlation established from rainfall and landslide data of the June 2008 rainstorm and are divided into three slope gradient ranges, viz. ≤15°, 15° to 25° & >25° (Fig. 8). The June 2008 rainstorm is the most severe rainfall event since the GEO began to collect rainfall and landslide data systematically in 1984. Based on the natural terrain landslide inventory established by the GEO, the average source area of a natural terrain landslide is about 70 m². If the landslide density is raised to about 14,000 no./km², it is expected that 100% of the natural terrain area would fail. Hence, the landslide density is capped at this level.

### 3 LANDSLIDE HAZARD

#### 3.1 Approach of Assessment

For emergency preparedness for landslides under extreme weather, the GEO adopts a scenario-based approach. Landslide impact corresponding to rainfall of notional return period of 10,000 years was predicted.

![Diagram](image)

Note: Solid lines represent the envelopment of the relations between 24-hour (in purple) and 3-day (in blue) PMP estimates against the drainage area sizes for the existing hydropower projects, respectively.

Fig. 7. Comparison of updated Hong Kong 24-hour PMP with PMP estimates of existing hydropower projects in China

#### 2.5 Uncertainties

It is stated in WMO (2009) that “the current knowledge of storm mechanisms and their precipitation-producing efficiency remains insufficient to allow precise evaluation of limiting values of extreme precipitation. PMP estimates, therefore, must still be considered approximations.”

The uncertainties on the PMP estimation mainly arise from i) limitation of the extent of the storm survey, ii) availability and quality of the rainfall and dew point data, iii) assumptions of meteorological similarity between Taiwan and Hong Kong for storm transposition and condition of saturated pseudo-adiabatic atmosphere for moisture maximization, iv) numbers and representativeness of base raingauge stations, v) resolution with respect to spacing of the raingauge stations and the grid size, and vi) procedures of generalization of the convergence components of the four Taiwan storms.

![Diagram](image)

Note: Normalized 24-hour rainfall is defined as location-specific maximum rolling 24-hour rainfall normalized with the corresponding mean annual rainfall at that particular location.

Fig. 8. Landslide density of natural hillsides vs normalized 24-hour rainfall based on June 2008 rainstorm

How far a landslide would travel downhill was estimated from a runout model. This governs whether the facilities in front of a hillside would be affected. The runout model was also derived from the landslide data of the June 2008 rainstorm (Fig. 9 and 10). Sensitivity analyses were conducted by assuming the proportion of mobile failures (viz. open hillslope failures with runout distance exceeding 100 m and debris flows along channelized catchments and topographic depression catchments with runout distance exceeding 200 m) to be twice that observed in the June 2008 rainstorm to account for possible increase in...
debris mobility in an extreme rainfall event.

Fig. 9. Runout model for open hillslope failures (Lau et al, 2012)

Fig. 10. Runout model for debris flows along channelized catchments and topographic depression catchments (Lau et al, 2012)

3.3 Man-made Slope Failure Models

The number of registered man-made slope failures was estimated based on the rainfall and geographical distribution of registered man-made slopes with the use of the rainfall-landslide correlations, which are divided into four types, viz soil cut slopes, rock cut slopes, fill slopes and retaining walls (Wong et al, 2014) as shown in Fig. 11.

Fig. 11. Correlations between landslide frequency and rolling 24-hour rainfall for soil cut slopes, rock cut slopes, fill slopes and retaining walls

Based on statistics of landslide records, it was assumed that 75% of the man-made slope failures would arise from registered man-made slopes; and that 17% of the man-made slope failures would affect buildings and 45% would affect roads. On the basis of the assumptions above, the number of landslides on man-made slopes affecting buildings or roads was estimated.

3.4 Assessment

Theoretically, the elliptical isohyets of the updated PMP could be centred at any location in Hong Kong with their major axis at any orientation for assessing landslide hazard. Fig. 12 shows an example of superimposing the centre of the PMP isohyets on Hong Kong Island with the orientation of major axis at E-W. In the study, Hong Kong Island was divided into grid cells of 1.2 km x 1.5 km. The centre of the PMP isohyets was superimposed at each grid cell with the major axis orientated at 4 different bearings (i.e. N-S, E-W, SE-NW, NE-SW). In each case, the numbers of landslides on natural terrain and man-made slopes affecting buildings or roads in the whole Hong Kong territory were estimated based on the models discussed above. The results corresponding to the worst case in terms of numbers of landslides affecting buildings or roads are shown in Table 2.

Table 2. Predicted numbers of landslides for scenario of extreme rainfall corresponding to 70% of the updated 24-hour PMP hitting Hong Kong Island

| Total No. of Landslides | No. of Landslides Affecting Buildings / Roads |
|-------------------------|---------------------------------------------|
| 50,000                  | 4,000 - 9,000                               |

Under this landslide scenario, the capacity of the existing Hong Kong emergency response system would be exceedingly overwhelmed, and the current mode of operation would become ineffective and inefficient in emergency management. This calls for development and implementation of a new strategy and measures for managing the emergency.

3.5 Uncertainties

The key uncertainties of the above assessment arise from i) extrapolation of the rainfall-landslide frequency correlations to high rainfall classes, ii) potentially higher debris mobility than that observed in June 2008 rainstorm, iii) possible change in landslide mechanism, and iv) impact of multiple failures under extreme rainfall conditions (e.g. 70% of the updated PMP).

In view of the above uncertainties, the numbers of
landsides predicted are treated as rough figures indicating the order of magnitude of the possible event, rather than precise scientific results.

3.6 Further Work

The GEO has recently completed a territory-wide rainfall-based landslide susceptibility analysis for natural terrain in Hong Kong (Lo & Ko, 2015). Further work on the scenario-based assessment incorporating the results of the above susceptibility analysis may be warranted.

4 SUMMARY

For an area of 10 km², the updated 24-hour PMP is estimated to be 1,510 mm. The updated PMP has been applied in a scenario-based assessment of landslides for the purpose of emergency preparedness. 70% of the updated PMP, which is roughly equivalent to a notional return period of 10,000 years, has been adopted as a scenario of landslides under extreme weather condition. Under this level of rainfall, it is expected that about 4,000 to 9,000 landslides affecting buildings or roads would occur in Hong Kong.

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