

Recent Developments in the Landslip Warning System in Hong Kong

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Abstract: Since the late 1970s, Geotechnical Engineering Office has been operating a Landslip Warning System in conjunction with the Hong Kong Observatory to forewarn the public of landslide risk during periods of heavy rainfall. The original warning criteria were improved in the early 1980s. Since then, a lot rainfall and landslide data have become available. A fundamental review of the relationship between rainfall and landslides was therefore carried out in 1999. This paper describes the application of the results of the review in the development of a set of improved criteria for the issue and cancellation of Landslip Warnings in Hong Kong.

1 INTRODUCTION

Landslip Warning and emergency services are integral parts of the slope safety system of the Geotechnical Engineering Office (GEO). The provision of Landslip Warning to the public during periods of heavy rainfall is a potentially effective way of reducing the landslide risk.

Landslip Warnings are issued by the Hong Kong Observatory (HKO) in consultation with the GEO when the recorded and forecast rainfall meets the prescribed warning criteria. A Landslip Warning System was established in 1977. The warning criteria have been revised several times over the years to take into account the changes in the number and conditions of the slopes, their geographic distribution in relation to the affected population and the experience gained from the operation of the system. The last set of Landslip Warning criteria was based on the 24-hour rainfall comprising a measured 20 hour rainfall plus a forecast 4-hour rainfall. A general Landslip Warning for Hong Kong was issued whenever the rainfall was expected to exceed 175 mm in 24 hours at the HKO or at certain other raingauges of the existing automatic raingauge system. Additionally, Landslip Warning might be issued when the rolling 60-minute rainfall exceeded 70 mm at any automatic raingauge on Hong Kong Island or Kowloon.

This set of warning criteria was derived from the work done in the early 1980s. A lot of rainfall and landslide data have become available since then. Also, owing to the changes in slope and population distribution, the types of facilities reported to have been affected by rain-induced landslides have changed to a large extent over the past 20 years. In the late 1970s and early 1980s, there were a lot of landslides affecting squatters. The Landslip Warning at that time mainly served to forewarn squatter residents of landslide risk during heavy rainstorms. With the Government's Squatter Clearance Programme,

especially that which recommends clearance on slope safety grounds since the mid-1980s, the number of squatters affected by landslides has been substantially reduced. The Landslip Warning is now being used as a general warning to the public, and emphasis is placed on the need for individuals to take personal precautions during heavy rainstorms. A public education and assistance programme is being implemented to complement the warning advisory and emergency services.

2 RAINFALL DATA AND CHARACTERISTICS

In the rugged terrain of Hong Kong, the distribution and intensity of rainfall during a rainstorm can vary dramatically with respect to both geography and time. To provide sufficient area coverage for a meaningful analysis of rainfall distribution, the HKO has installed a network of raingauges, which, in 1998, comprised 24 automatic and 51 manual raingauges at 68 stations. A number of manual raingauges and three automatic raingauges have also been installed by the Water Supplies Department and the Drainage Services Department respectively. The 'principal' raingauge is located at the HKO's headquarters in Tsim Sha Tsui, and a continuous rainfall record has been kept at this location since 1884 (except in the period 1940 to 1946).

Since 1978 the GEO, in cooperation with the HKO, has established an automatic raingauge system which transmits real-time rainfall data via telephone lines to the GEO and the HKO at five-minute intervals. The locations of the GEO automatic raingauges were selected to supplement the network of other types of raingauges and to provide specific information in areas of particular geotechnical interest. The GEO raingauge system was upgraded in 1999, and now have 86 automatic raingauge stations (Pang et al. 2000).

Heavy rainstorms in Hong Kong are generally

associated with either low pressure troughs or severe tropical cyclones. The more significant rainstorm events (rainstorm with a rolling 24-hour rainfall of over 300 mm anywhere in Hong Kong or that which has resulted in fatal landslides) in the period 1984 to 2000 are listed in Table 1.

Table 1. Significant rainstorm events in the period 1984 to 2000

Period of Rainstorm Event	Maximum Rolling Rainfall		Consequence		
	24-hr (mm)	1-hr (mm)	Number of Landslides Reported to the GEO ⁽²⁾	Number of Persons Killed	Number of Persons Injured ⁽³⁾
29-30/7/1987	314	73	111	0	3
20-21/5/1989	552	51	340	2	3
8/5/1992	385	110	350	3	5
16/6/1993	285	91	108	1	5
26/9/1993	374	58	104	0	0
4-5/11/1993	742	94	377	0	0
21-24/7/1994	954	186	120	5	4
5-6/8/1994	380	76	21	1	0
12-13/8/1995	468	82	70	3	6
2-3/7/1997	799	125	118	1	9
8-9/6/1998	562	98	96	0	0
22-26/8/1999	565	121	276	1	13
16-17/9/1999	384	90	35	0	0
14-15/4/2000	526	109	64	0	0
24-27/8/2000	364	127	77	0	1

Notes: (1) This Table includes events with a rolling 24-hour rainfall of over 300 mm anywhere in Hong Kong or that which resulted in fatal landslides.

(2) The number corresponds to landslides known to have occurred during the period of the rainstorm event. There were a few landslides which occurred before and after this period.

(3) Cases involving only very minor injuries (persons suffering simply from shock or persons discharged soon after receiving minor treatments at the hospital) have not been included in this Table.

3 LANDSLIDE CHARACTERISTICS

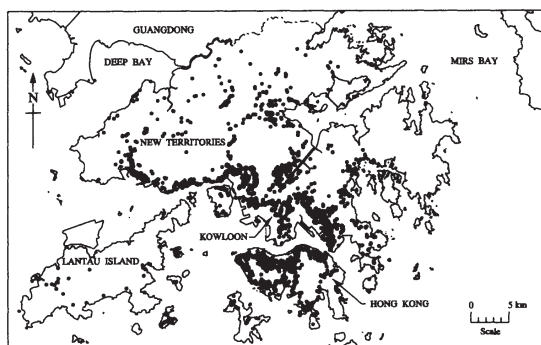
Over 6000 landslides have been reported to the GEO since 1982. Amongst these, about 10% were 'major' incidents, which are defined as landslides with a failure volume greater than or equal to 50 m³. There is a trend of the percentage of major incidents increasing with the number of landslides reported (Sun et al. 2001).

Table 2. Number of landslip warnings issued and associated landslides in the period 1977 to 2000

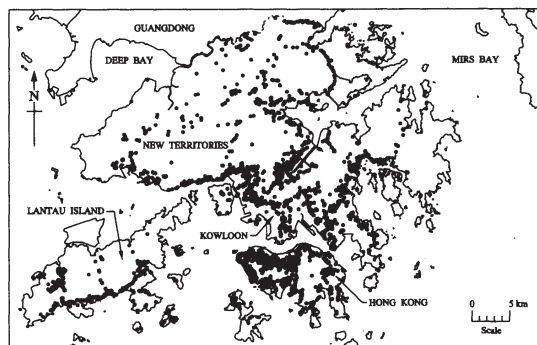
Year	Number of Landslip Warnings Issued	Number of landslides known to have occurred on the days of Landslip Warnings	
1977	0	Detailed records not available	
1978	2		
1979	2		
1980	0		
1981	0		
1982	3		
1983	4		
1984	3		26
1985	3		58
1986	5		112
1987	3	113	
1988	1	41	
1989	3	464	
1990	3	30	
1991	1	9	
1992	3	393	
1993	4	366	
1994	4	249	
1995	6	184	
1996	2	30	
1997	8	325	
1998	1	88	
1999	2	311	
2000	6	175	
Annual Average (1984-2000)	3.4	175	

The locations of the reported landslides in the period 1982 to 1997 are shown in Figure 1. It can be seen that the landslides are distributed mainly along lineaments, some of which correspond to major roads. The distribution patterns of minor landslide incidents (i.e. those with a failure volume less than 50 m³) in the 1980s and the 1990s are fairly similar, but those of major landslide incidents are quite different. In the period 1982 to 1989, there were a lot of major incidents in the western and central New Territories, many of which are around Castle Peak Road and Route Twisk. These were mainly due to two heavy rainstorms, in May 1982 and May 1989 respectively. The large number of major landslide incidents in Lantau and Shatin in the period 1990 to 1997 was mainly a result of the November 1993 rainstorm and the July 1997 rainstorm respectively.

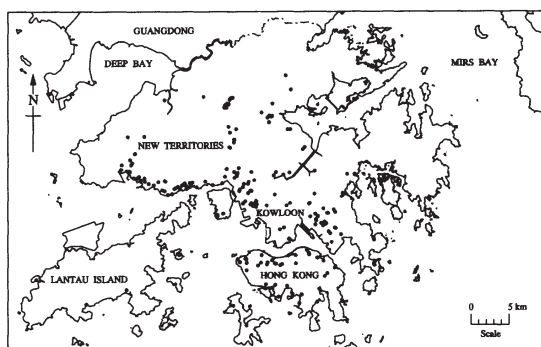
The number of Landslip Warnings issued since 1977, along with the total number of landslides that



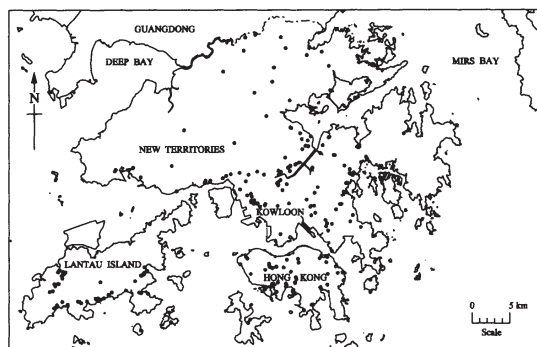
Spatial Distribution of All Landslides Reported to the GEO in the Period 1982-1989



Spatial Distribution of All Landslides Reported to the GEO in the Period 1990-1997



Spatial Distribution of Major Landslides ($\geq 50 \text{ m}^2$) Reported to the GEO in the Period 1982-1989



Spatial Distribution of Major Landslides ($\geq 50 \text{ m}^2$) Reported to the GEO in the Period 1990-1997

Figure 1. Spatial distribution of landslides

occurred on the days of Landslip Warnings (since 1984), are summarised in Table 2. On average about three to four Landslip Warnings were issued each year. The number of landslides that occurred on the days of the warnings ranged from around ten in small (in terms of intensity/area coverage) rainstorm events to over 300 in big rainstorms, the average number being about 50. There were some landslides that occurred within one or two days after cancellation of Landslip Warning when the rainfall intensity had diminished. The remaining ones were isolated landslides generally of small scale, which sometimes occurred in periods of light rainfall or were triggered by other causes such as construction activities or leakage/bursting of water mains. Landslip Warnings are generally issued for rainstorm events when a fair number of landslides (more than ten) are anticipated.

4 RESEARCH ON RAINFALL AND LANDSLIDE RELATIONSHIP

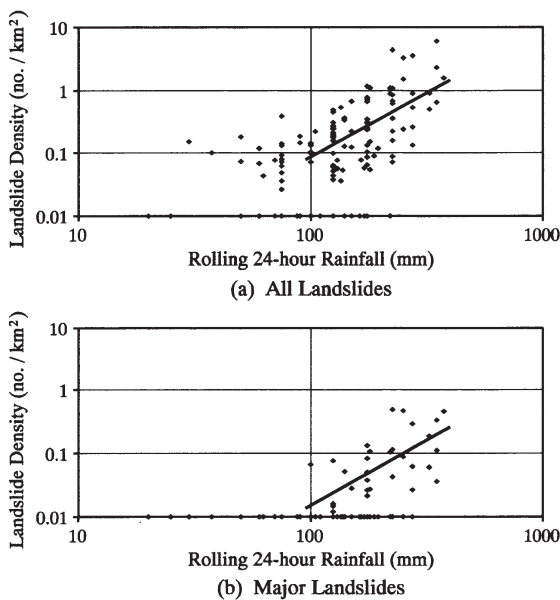
Brand et al (1984) reported on the work carried out in the early 1980s for the development of the set of Landslip Warning criteria used since then. In that research, rainfall data covering a period of about 20 years were analysed. Data on the time of landslide occurrence used were based on the records of the Fire

Services Department, which were generally events causing casualties in squatter areas. The authors concluded that (i) the large majority of landslides in Hong Kong were induced by localised short duration rainfall of high intensity, and these landslides took place at about the same time as the peak hourly rainfall, and (ii) a (clock hour) rainfall intensity of about 70 mm/hour appeared to be the threshold value above which landslides that resulted in many casualties occurred (i.e. consequence-based criteria).

Premchitt (1985) found that at the time of onset of most "significant" rainstorm events (i.e. rainstorms which resulted in ten or more reported landslides in a day in the whole of Hong Kong) in the period 1964 to 1982, the lower limit of the maximum rolling 24-hour rainfall measured at the HKO rain gauge was about 175 mm. Premchitt (1991) conducted analyses for additional rainstorm events. These findings formed the basis of the Landslip Warning criteria in the late 1980s and most years of the 1990s.

With the clearance of hillside squatters, improvement to the design and construction of new slopes and retrofitting of existing substandard slopes brought about by GEO's Slope Safety System, and changes in slope and population distribution in the last twenty years, it is expected that the correlation between rainfall and landslides reported would have changed with time. For example, the number of

landslide casualties has significantly reduced in the past fifteen years. The wealth of data on rainfall and landslides collected since 1984 through the extensive raingauge network and detailed recording of landslide incidents by GEO's professional staff have allowed a fundamental review of the relationship between rainfall and landslides reported to be carried out.



Notes: (1) Rolling 24-hour rainfall data corresponds to those at the vulnerable areas at the time when the maximum rolling 24-hour rainfall was recorded for the rainstorm event.
 (2) Data used cover the period 1984 to 1996.

Figure 2. Correlation between landslide density and rolling 24-hour rainfall at vulnerable areas in Hong Kong (Pun et al. 2001)

Figure 1 shows that some geographical areas of Hong Kong have more reported landslides than others (i.e. these are areas which are more 'vulnerable' at times of big rainstorms). A study was carried out to derive the relationship between rolling 24-hour rainfall and landslide density (defined as the number of reported landslides per unit area) for the areas with lots of reported landslides (called 'vulnerable areas'). The key findings of the study are reported by Pun et al (2001). It is found that the landslide density of the vulnerable areas has a reasonable correlation with rolling 24-hour rainfall in any given rainstorm (Figure 2). For a rolling 24-hour rainfall of less than 100 mm, the landslide density is negligible, ranging from 0 (i.e. no landslides) to about 0.2 no./km². The landslide density increases significantly for rainfall greater than 100 mm.

The effect of high-intensity short-duration (1-hour) rainfall on the extent of landslides was also examined. It is noted that in the period 1984 to 1997 there were

rainstorm events in which more than 70 mm of rain in 60 minutes was recorded but this did not result in many landslides (e.g. the 12 July 1994 rainstorm). On the other hand, there were many cases in which the recorded maximum rolling 60 minute rainfall was less than 70 mm or the high intensity rainfall covered only a small area, but there were a lot of landslides (e.g. the 22 July 1994 rainstorm). The above shows that 70 mm rainfall in 60 minutes is not a necessary nor sufficient condition for widespread landsliding in Hong Kong.

5 TIME LAG BETWEEN LANDSLIP WARNING AND LANDSLIDE OCCURRENCE

The landslide data with recorded times of failure were also analysed as part of the study to obtain the frequency distribution of the time lag between the issue of Landslip Warning and landslide occurrence for individual reported incidents. The results together with the times of reporting of the failures to the GEO provided useful information for establishing a set of criteria for cancellation of Landslip Warning.

Thirty-one rainstorms from 1990 to 1997 (with Landslip Warning actually issued) were selected for frequency analysis. For each rainstorm selected, a cumulative frequency distribution curve of the time between the time of issue of Landslip Warning (using the proposed revised warning criteria described below) and the time of occurrence of landslides was plotted (Figure 3). Rainstorms with less than five incidents were considered not significant/representative for frequency analysis and were excluded. The cumulative frequency curves in Figure 3 can be broadly categorised into two groups based on their shape. In the first group, heavy rainfall occurred and the cumulative frequency quickly increases shortly after the issue of Landslip Warning. Generally, these are events with one notable peak in the hourly rainfall distribution. For the other group, the cumulative frequency does not rise significantly for some time after the issue of warning. A sharp rise in cumulative

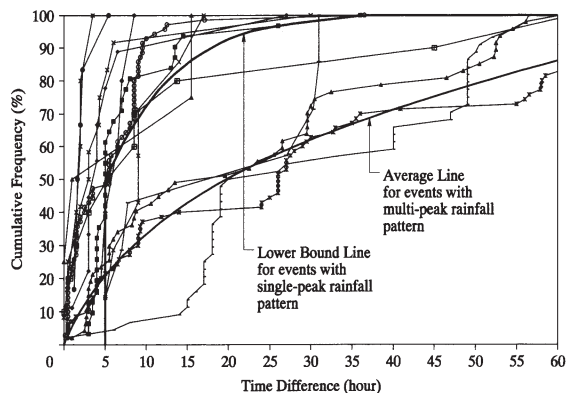


Figure 3. Cumulative frequency distribution of time difference between issue of landslip warning and occurrence of landslides

frequency occurs only after a certain time when a significant amount of further rainfall took place, acting as a second or even third trigger to the occurrence of landslides. Examples of these multi-peak events are the rainstorms of 21-24 July 1994, 12-13 August 1995 and 2-3 July 1997.

6 APPLICATION IN THE LANDSLIP WARNING SYSTEM

Rolling 24-hour rainfall is found to be the most suitable and convenient parameter for predicting the number of reportable landslides in the vulnerable areas of Hong Kong. The best-fit line in Figure 2 can be used to predict the number of reportable landslides in each of the vulnerable areas when Hong Kong is hit by a rainstorm having a maximum rolling 24-hour rainfall greater than 100 mm. When the rolling 24-hour rainfall at any location is less than 100 mm, the landslide density is likely to be negligible and can be assumed to be zero without seriously affecting the accuracy of prediction of the total number of landslides in Hong Kong for significant rainstorms. The estimated total number of landslides in Hong Kong is simply the sum of the predicted numbers of reportable landslides in the different vulnerable areas. A Landslip Warning may be issued when the estimated total number of landslides exceeds a certain critical value (Warning Level). It is considered appropriate to adopt ten reportable landslides as the Warning Level. This is based on the observation that on average about 10% of the past reported landslides were major incidents in a rainstorm and that casualties were generally caused by major landslides only. Adopting this approach would mean that Landslip Warning would be issued when one or more major landslides are predicted. Figure 4 depicts the revised criteria for the issue of Landslip Warning. The development of rainfall in the rainstorm event on 24 August 2000 is also shown to illustrate the application of the criteria.

In view of the scatter in data in Figure 2, it is expected that there will be uncertainties in the number of landslides estimated using the best-fit line. The actual number of landslides reported may be very different from that predicted for the area represented by an individual rain gauge. However, for a rainstorm covering a large area, the error in the total number of reportable landslides predicted will be small due to 'averaging out' effect because the number of landslides may be over-predicted in some areas and under-predicted in the other areas. For the issue of Landslip Warning, it is required to predict just whether the number of reportable landslides is more than ten or not, rather than a precise number of landslides. The error in the prediction is therefore not of significance, except perhaps in cases when the predicted number is less than say 20.

In operating the revised criteria, the rolling 24-hour rainfall to be used includes the 21-hour recorded rainfall and the rainfall amount forecast by the HKO for the next three hours. Cheung & Lai (2001) presents recent developments in rainfall nowcasting techniques at the HKO.

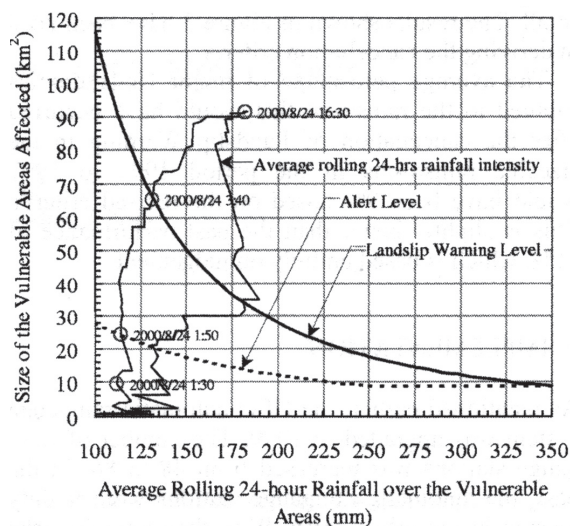


Figure 4. Revised criteria for the issue of landslip warning

The revised warning criteria have been tested using data obtained in 74 sizeable rainstorms in the period 1990 to 1997. They give very good results, in that Landslip Warnings could be issued more reliably and more timely (before major landslides occurred). Compared with the previous Landslip Warning criteria, the number of missed events (i.e. events with ten or more reported landslides but for which the criteria could not trigger the issue of warning) would theoretically reduce from six to one assuming perfect rainfall forecast. The theoretical number of false alarms would reduce from twelve to six. In the worst case scenario that a Landslip Warning is issued every time the Alert Level is met (i.e. the additional amount of rainfall is forecast to be high enough to trigger a warning in all cases), there would have been twenty false alarms but no missed events.

Of the past sizeable rainstorms examined, the average percentage of major landslides attributed to the rainstorm that would have occurred before the issue of Landslip Warning based on the revised criteria would be between 9% and 18%, corresponding to the best case scenario of perfect rainfall forecast and the worst case scenario of no forecast (i.e. issue of warning only when the criteria are met) respectively. This is better than the actual performance of 20% in past Landslip Warnings in the same period.

To cancel a Landslip Warning, the number of landslides (particularly major landslides) likely to

occur after the cancellation must be small. Criteria for cancellation of Landslip Warnings have been developed based on the principles that (a) both the rainfall recorded in the past few hours and that forecast for the next few hours should be small, and (b) the time since the issue of the Landslip Warning should be sufficiently long such that the number of landslides likely to occur after the cancellation is small. The results shown in Figure 3 have been used in deriving the cancellation criteria.

The average percentage of major landslides attributed to the rainstorm that would have occurred after the cancellation of Landslip Warning in the sizeable rainstorms in the period 1990 to 1997 would have been 9% based on the revised criteria. This is slightly better than the past performance of 11%, which is based entirely on judgement.

7 IMPLEMENTATION

As mentioned earlier, the GEO automatic raingauge system was upgraded in 1999. The number of raingauge stations was increased from 48 to 86. In the past, the automatic raingauge stations were mainly located in the urban areas. With the upgrading, the coverage of the raingauge network was greatly improved to cover the previously rural areas which are now developed as well. This enhances the capability of the rainfall network in delineating and tracking the spatial distribution of rainfall and its area coverage over Hong Kong in real time. To facilitate decision-making for the issue and cancellation of Landslip Warning, the revised warning criteria have been programmed into the upgraded GEO raingauge system software and information on landslide incidents reported to the GEO is updated regularly through a computerised Landslip Information Handling System.

The revised Landslip Warning criteria were tried out in 1999 and implemented since the wet season of 2000. By strictly following the criteria there would have been no missed event in 1999 and 2000. However, there were three false alarms, owing to the high uncertainties in the landslide prediction capability at the low rainfall intensity levels encountered (especially in the beginning of the wet season when the slopes are 'wetted' for the first time in the year) (see Pun et al. for discussion on antecedent rainfall).

8 PLANNING FOR EXTREME LANDSLIDE EVENT SCENARIOS

As part of the work to improve the landslide emergency preparedness planning for Hong Kong, a study was carried out by the HKO for the GEO to review the probable maximum precipitation for Hong Kong (Chang & Hui 2001). The results of the work

have been used to develop possible extreme landslide event scenarios for a chosen extreme rainstorm event, for review of GEO's landslide emergency preparedness plan (Sun et al. 2001; Au Yeung et al. 2001).

9 CONCLUSIONS

With the availability of abundant rainfall and landslide data since 1984, it is possible for the GEO to carry out a fundamental review of the relationship between rainfall and landslides. A number of studies have been conducted using the data. Useful results have been obtained from these studies, which have allowed the development of more reliable criteria for the issue and cancellation of Landslip Warnings. Continuous improvement is being made to the Raingauge and Landslip Warning System, through regular review of the rainfall and landslide correlations, review of the effectiveness of the public education programme and warning messages, and improvement of the landslide emergency service operation.

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