PROBLEMS AND ACCURACY OF PHOTOGRAMMETRIC VOLUME ESTIMATION OF LANDSLIDE INDUCED BY EARTHQUAKE

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ABSTRACT

On Sep.21 1999 a strong earthquake with magnitude 7.3 on the Richter scale occurred in the central part of the island China Taipei. More than 2400 people were killed. Earth surface deformation and landslide occurred at many places along the Chehlungpu Fault. The biggest landslide occurred at the Tsaoling Mountain (1,234m). Its south face slid down into the Chingshuei Creek valley. Three months after the earthquake, aerial photos were taken to analyze the extent of damages. We used these photos for estimating the volume of the landslide. Normally volume calculation is a trivial work in Photogrammety. But in our case some difficulties were encountered, like how to get ground controls from inaccessible area, how to estimate the accuracy of the calculated volume etc. This paper describes how these problems are and how they were solved.

1 INTRODUCTION

China Taipei is a small island (ca. 36000 sq.km.) located less than 200km east off the Chinese mainland and right on the collision line of the Euro-Asia Plate and the Philippine Sea Plate. This collision line is part of the earthquake belt around the Pacific Rim. Several major faults running approximately in the north-south direction induced frequently earthquakes (Chen,1999).

In the very early morning at 1:47 a.m. of the September 21, 1999 a very strong earthquake with magnitude 7.3 on the Richter scale occurred in the central part of China Taipei. More than 2400 people were killed and over 10,000 buildings were destroyed. Earth surface deformation and landslides occurred at many places along the Chehlungpu Fault. The biggest landslide was at Tsaoling Mountain. The south face of the mountain slid down into the Chingshuei Creek valley (Fig.1).

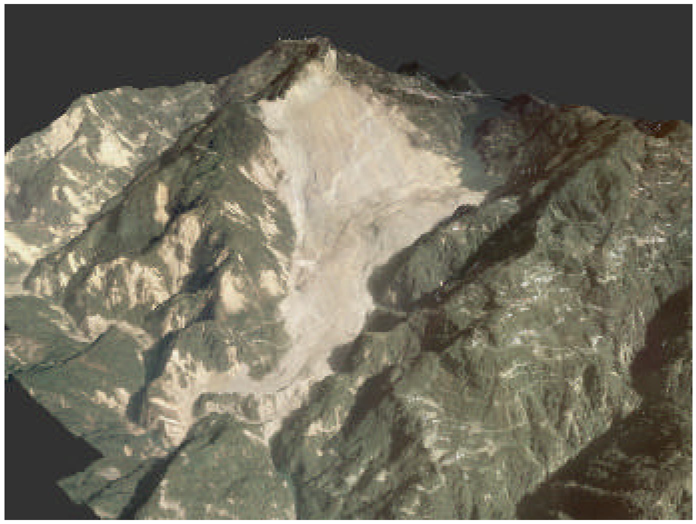

Figure 1. Perspective view of Tsaoling Mountain landslide area.

Tsaoling Mountain is 1234m high and lies at the north side of Chinshuei Creek, a tributary stream of the largest river Droushuei of China Taipei. Partly of the mountain is covered by thick vegetation of trees and bushes. A few people lived in that region and had built some houses. The only road leading to that region was destroyed during the earthquake.

Due to its weak geological structure, Tsaoling Mountain has a history of landslides in the past (Chen,1999). The landslides were induced some times by earthquake and some times by heavy rainfall. This time, the strong earthquake induced a landslide of an area of approximately 530ha., not including small landslides surrounding this major site. Three months after the earthquake, in December 1999, aerial photographs were taken for analyzing the extend of damage. One major task was to estimate the volume of the landslide photogrammetrically.

Two flight lines had been flown in the north-south direction. The forward overlap was 60% and the side overlap was 30%. In order to increase the interpretation capability, positive color film from Agfa was used. The camera used was a LMK1000 with 15cm focal length. The flight height was 3500m above sea level. Since the peak of Tsaoling mountain is 1234m and the lowest creek valley is 500m, the photo scale for the valley is approximately 1/20000, for the mountain peak is approximately 1/17000.

Official orthophoto maps and digital elevation model (DEM) at 40m grid spacing of that region before the earthquake were available. Theoretically, if new DEM after the earthquake could be derived from the aerial photos, then, by comparing the old DEM with the new DEM, the amount of landslide volume should be able to be calculated. At the first glance, this looks like a very trivial work in Photogrammetry. Yet there are a few problems associated with landslide volume estimation in mountainous area after earthquake.

First, the only road leading to the area was destroyed after the earthquake, which made the area inaccessible. Second, even if people could get there, it would not be possible to set up enough signalized ground control points for aerial triangulation in time and money, because the region is mountainous and mostly covered by thick sub-tropical woods, which makes it very difficult to access to. Therefore no ground control points in conventional manner were available for the aerial triangulation. Ground control points have to be found from the old orthophoto maps and DEM, which results in difficulty in estimating the quality of the ground control points. Third, since the quality of the old orthophoto and DEM is unknown, it is very difficult to estimate the accuracy of the landslide volume calculated.

2. ARIAL TRIANGULATION AND DEM MEASUREMENT

There were totally 17 photos used for aerial triangulation. Six of them were actually used for measuring the volume of the landslide. In order to correctly calculate the volume of the landslide, our photogrammetric block had to be fitted onto areas outside the landslide, where no landslide occurs. That means, for areas outside the landslide area, the new DEM had be the same as the old DEM. This could be achieved in two ways. One way is simply to use the outside areas, instead of points in these areas, as ground controls for the aerial triangulation. The other way is to follow the conventional way of using ground control points. The first way has been researched by (Jaw,2000) but was still not available for practical usage. Therefore we had chosen the second way.

All ground control points had to be determined from the existing old orthophoto maps produced in 1980, almost 20 years ago. The orthophoto maps are partly in scale 1/5000 and partly in 1/10000 associated with a DEM. The DEM had an uniform grid spacing of 40m and was produced from the same aerial photos that had been used to produce the orthophoto maps. The DEM.

The aerial triangulation was carried out digitally and automatically on a Leica-Helava digital photogrammetric workstation (DPW). The stereo measurement of the DEM was carried out on Leica SD2000 analytical plotters.

3.1 Control Points Determination

After elaborate searching in the old orthophoto maps and in the new aerial photos, some building corners, farmland corners, road corners and road junctions were found recognizable in both These points should be used as ground controls, but two difficulties arose.

First, although the horizontal position of a distinguished point could be easily read out directly from the orthophoto maps, the height of that point is not easily to get. Because, height information is implied in contour lines, not directly expressed for each individual point. Only through interpolation, one can get the height for each individual point. Besides, it is impossible to get height for building corners, since heights of buildings are not expressed in orthophto at all.

The second difficulty was that, clearly definable points was too few for a good control of the block in height. It is well known in Photogrammetry that, although only a few horizontal control points are enough to control the scale and the azimuth of a photogrammetric block, but a lot more height control points are needed to guarantee a close fitting of the block to the existing ground surface, especially in the case of 30% side-overlap between the strips. Since the central part of our block covered the landslide area that had no matching to the old orthophoto, enough height control points had to be found from the surrounding areas.

The difficulties were solved in following ways. For those ground features like road corners or farmland corners that in the nature lie on the earth surface, their height could be derived more accurately from the old DEM. With known horizontal coordinates from the maps the height could be interpolated from the DEM automatically.

As for building corners, since there is no way to get building height from the orthophoto maps, they could only serve as horizontal control points only. Yet it is worthy to mention that building corners are usually more accurately and more reliably to be recognized than o ther features. Few of them are enough to control the whole photogrmmetric block in horizontal very well.

The problem of getting enough height control points was solved by interpolation in the old DEM. Obviously, when a point feature is located on a relatively flat ground, the error in horizontal position will not affect its height. Therefore we could find more height control points from places where the ground surface is relatively flat, without taking too much consideration of whether the points are sharply recognizable or not.

Our strategy is to divide ground control points into two categories. One contains horizontal control points only. The other one contains height control points only. All points that are accurately recognizable in horizontal position but not in height belong to the first group. Points that are not accurately recognizable in position but lie on flat ground belong to the second group.

We have also notice that, within each group, points could have different accurate characteristics. For example, building corners used as horizontal control points are more accurate than farmland corners.

Therefore within each category we have assigned different accuracy for different type of points.
The horizontal accuracy was estimated by repeated measurements. The height accuracy was estimated posterior and iterative through the aerial triangulation itself. Since such kind of estimation could not be accurate, it is meaningless to differentiate the points into too many accuracy classes. For simplicity, we have assigned 2 accuracy classes for horizontal control points and 2 classes for height control points. This rough estimation is of course not very accurate. But it is still better than treating all points as equally weighted in the aerial triangulation.
In this manner we have picked up 17 horizontal control points and 20 height control points. For only two flight lines with only 17 photos this number of control points is far more than needed. By using so many ground control points, especially in the heightcontrol, a close fit to the existing DEM surface for the region outside the landslide area could be expected

3.2 Aerial Triangulation

The aerial triangulation had been done digitally. The color positive photos were scanned in B/W with 25ì m resolution on a Leica DSW200 scanner. The scanned digital images were then imported into the DPW for aerial triangulation. Due to large relief in the mountain region, the automatic image matching was not very successful, a large num ber of tie points have to be measured manually.
The on-line measured and preliminary error-checked measurements of tie points were then imported to the PAT-B bundle adjustment program for the final aerial triangulation. The maximal residuals on the horizontal ground control points was about 6m, which corresponds to 0.6mm on the 1/10000 orthophoto map. This amount is quite reasonable for such scale of orthophotos. The maximal height residual was about 5m, which, in considering the 40m grid spacing of the old DEM, is also reasonable. In general we can say that the whole photogrammetric block had been fitted to the old map and the old DEM in a reasonable manner.

2.3 Landslide Volume Measurement

In order to get the highest quality, measurement had been done on analytical plotters using the original color positive film. For this kind of mountainous area, we did not measure the grid point directly. Instead, we have measured the contour lines together with the geomorphologic structure lines and break lines and computed the DEM from these data. This is the best way to capture mountain surface topography. Because for steep terrain, contour line following is more reliable and accurate than direct grid points measurement. The measured data were imported into the SCOP program for computing the DEM with the same grid spacing of 40m like the old DEM.
Here we would like to point out that part of the slid down mass fell into the Chingshuei Creek, so that a lake is formed on the upstream side. The depth of the lake is estimated to be 50m (Chen,1999). The under-water part could not be measured by photogrammetric method. Therefore during the calculation of the DEM we just simply excluded this part.
The difference between the DEMs before and after the earthquake gives the change of the earth surface. We subtracted the new DEM from the old DEM. Therefore a positive difference would mean that mass had been removed from the original ground surface. A negative difference would mean that slid down mass had been piled up at that place. The resulted positive difference is 123 million cubic meter and negative difference is 126 million cubic meter. That means 123 million cubic meter earth mass had slid down.
From these figures we see that the piled up mass is more than the slid down mass. This phenomenon might be explained by the fact that the piled up mass is less dense than the slid down mass. Remember that we have excluded the part that was covered by water. There must be certain amount of slid down mass under the water surface. Considering this, the slid down mass must be even larger than the above calculated 126 million cubic meter.

3. ERROR ANALYSIS

To answer the question how accurate is the calculated volume, we have to analyze first what are the sources of errors. First of all, the volume is calculated by subtracting the new DEM from the old DEM. Therefore the accuracy of the estimated amount depends of course on the accuracy of the two DEMs.

The old DEM together with the orthophoto maps were produced by the government forestry agency. There is no information available concerning the accuracy. We know only that the DEM was produced by using the same aerial photos as producing the orthophoto maps. Theoretically it is not difficult to estimate the achievable measuring accuracy of bare ground surface in stereo models. But the accuracy of DEM is much more complicated.

First, since the area is mountainous and partly covered by thick vegetation of sub-tropical trees, the error from judging where under the vegetation is the ground surface, is much larger than the pure stereo measuring error. Second, the old DEM has 40m wide grid spacing, even the ground is bare, a lot of ground details between the grid points are missing, especially when the ground surface is hilly. The amount of these kinds of errors could of course not be accurately estimated.

The possible range of the accuracy of the old DEM was derived therefore indirectly from another project. In one similar case of mountainous area with vegetation, the accuracy of the photogrammetrically measured DEM had been estimated through repeated measurements and field check. That DEM has 20m grid spacing and was measured by a very experienced operator from 1/20000 scale photos. The accuracy was estimated to be approximately 2m (standard deviation). We could not expect that the operators for producing the official DEM could achieve the same accuracy as this experienced one. Besides, the old DEM has a wider grid spacing of 40m. Therefore we had estimated that the accuracy of the old DEM would be something between 3m to 4m depending on the density of the vegetation and on the steepness of the terrain surface.

To estimate the accuracy of the new DEM we have to follow the production process to see where errors come from. First, the DEM is calculated from the measured contour lines and geomorphologic lines in stereo models. The pure measuring accuracy for height of clearly defined ground points in stereo model is well known to be higher than 0.01% (Schwidefsky, 1976). In our case of 3500m flying height, it is approximately 0.3m. But this number is valid only for clearly defined terrain points. It has neither considered the above mentioned error caused by vegetation nor the error from the exterior orientation of the stereo model itself. Luckily, the landslide area has no vegetation. Only a small portion of the outside area with trees is included in the computation. Therefore the influence of vegetation on the new DEM is much smaller than that on the old DEM. On the other hand, the accuracy lost due to wide grid spacing could not be avoided. This part of influence could be estimated through comparing the actual measured contour lines with contour lines interpolated from the 40m grid spacing DEM. The estimated accuracy was less than 1m for bare soil surface. But since a small part covered by trees was also included in the computation, we had assigned 1m for the measuring accuracy of the new DEM.

The last error source in our case is the exterior orientation error of the stereo model. The stereo model was restituted by data from aerial triangulation. But since the quality of the ground control points was very poor, the accuracy of the aerial triangulation could not be good. Therefore the orientation of the model was also not error-free. Any error in the height would result a wrong leveling of the model and causes error in the height of contour line measurement that in turn causes error in DEM.

Since error in horizontal position has lesser influence on the height, and since our main concern here is the height accuracy of the DEM, therefore for the following error analysis only height needs to be considered.

Let us now analyze the error propagation following the direction of production process, namely from the aerial triangulation to stereo model restitution.

According to (Schwidefsky, 1976) accuracy of aerial triangulation depends on the so-called block parameters. They are the number and the distribution of control points, the overlapping of photographs in the strips and across the strips, the number and distribution of tie-points, the number of strips, the focal length of the aerial camera, etc.. In our case of two strips with 60%forward overlap and 30% side overlap, the expected accuracy of the height of the tie points after aerial triangulation depends mainly on the number and distribution of height control points, which can be expressed as

ì = (0.93 + 0.19i) ó (1)

where i is the distance (expressed in number of air bases) between chains of height control points, and ó is the accuracy of the measured image coordinate. In our case the average i is about 3, Eq.(1) then gives 1.5ó. The accuracy of the image coordinates was estimated posterior after the bundle adjustment and was 9ì m. Thus, when the height of ground control points were error-free, the theoretical height accuracy of the tie points after aerial triangulation would be 15ì m (0.3m on the ground). But our ground control points were picked up from orthophoto maps and DEM. They are by far not error-free. For some of them we have an estimated height accuracy of 2m. This kind oferror acts as datum error. It deforms the block as a whole, independently from the block formation. For example, a constant +2m height error on all height control points would raise the block about 2m. Therefore we could treat this kind of error as independent from Eq.(1) .Of course the errors of our ground control points are random, not constant. Therefore we have to use error propagation to estimate their influence on the adjusted tie points.

If we see the whole block as a rigid 3D model, The way that the height errors of the ground control points affect the adjusted tie points is similar to a single stereo model affected by it pass point errors. Therefore the error analysis for a single model could be used for analysis of the error of a whole block. In (Wang, 1990) a simple case has been given to calculate the height accuracy of any points in the stereo model after absolute orientation with erroneous pass points. When a minimal number of 3 height control points are used, the error propagation gives a weight reciprocal in height for any point with the coordinates (x,y):

$$Q_{zz} = \frac{1}{2} + \frac{3x^2}{2b^2} + \frac{y^2}{2d^2} - \frac{x}{b} \qquad (2)$$

in which b is the base (model width), d is the half length of the model.

We can use the 6 Von Gruber points to represent the whole model. By giving the 6 points following coordinates : (0,0), (b,0), (0,d), (b,d), (0,-d), (b,-d), we have Q_{zz} equals 0.5, 1.0, 1.0, 1.5, 1.0, 1.5 respectively. The average is 1.04 or nearly 1. That means when the absolute orientation of a model is affected by erroneous height control points, the height of that model will have an accuracy that is almost of the same amount as the accuracy of the ground control points themselves. This conclusion is derived from the simple case of single model. When a block is made from many well connected models, it could be seen as a single model. In this case, similar conclusion could be applied to the block. Therefore for our case we had assumed that the accuracy of the stereo models is about the same as the accuracy of the height control points, which was 2m in worst. Comparing this 2m accuracy with the pure measuring accuracy of 0.3m derived above, we can see that the error of the new DEM is dominated by the control point error, not by the measuring error in the stereo model.

In summary, we had two main error sources for the new DEM. The first one was the DEM measuring accuracy in stereo models, which was estimated to be 1m. The second one was the accuracy of the stereo model itself, which was estimated to be 2m. Both have been considered to be independent and additive. Therefore the final accuracy of the new DEM would be $\sqrt{1.0^2 + 2.0^2} = 2.2m$.

Since the volume of landslide is calculated by subtracting the new DEM from the old, the accuracy of the subtracted height change should be calculated by the law of error propagation for difference computation. From the above estimated accuracy of 3m to 4m for the old DEM, the error propagation gives the accuracy of the height difference to be 3.7m to 4.6m. Since this estimation was not very accurate, we have just rounded it to 4m to 5m.

The volume is calculated by multiply the average height difference within each grid by its area of 40mX40m. Therefore the accuracy of the estimated volume is calculated by multiplying the accuracy of height difference with the total area of the DEM. Since the total area of landslide is 530 ha, the accuracy of the total estimated volume would be something between 530ha X 4m to 530ha X 5m, which is 21 to 27 million cubic meters.

5. COCLUSIONS

The main problem associated with the photogrammetric volume estimation of landslide induced by earthquake in mountainous region is that the landslide region is difficult to access to, because the road leading to the region is destroyed. If the volume of the landslide has to be estimated in short time after the earth quake, it is not possible to set up conventional ground control points for the aerial triangulation. When the ground control points have to be picked up from old orthophoto maps and old DEM's with little information about the accuracy, it is very difficult to estimate the accuracy of the calculated landslide volume. In this research, sources of errors for calculating the volume were analyzed. For each different kind of error source, proper method has been found to estimate its accuracy. Sometimes method of repeated measurements could be used, sometime indirect inference from other cases has to be used to derive accuracy estimations.

Since the estimated landslide volume is 123 million cubic meters, and the estimated accuracy of 21 to 27 million cubic meters is about 17% to 22% of the estimated volume, we can see that the photogrammetrically estimated landslide volume is not very accurate. From the above error analysis we can see that the main reason for this bad accuracy is that the old orthophto maps and DEM have very poor quality, since the whole computation of landslide volume was based on them as geodetic datum. If, for example, the old DEM had 20m grid spacing instead of 40m and had an accuracy of 1m, than the accuracy of the estimated landslide volume would be only 10 million cubic meters that is only 8% of the estimated landslide volume.

Here we would like to point out that the accuracy of the calculated volume is independent from the volume itself. That means as long as the area of the landslide region remains the same, the larger the slid mass is, the smaller is the relative error in percentage of the total volume.

Several means could be used to increase the accuracy. The first one would be to select ground control points directly from the original old aerial photos instead from the orthophoto maps and the DEM. By doing so, the error of identifying points and interpolating in DEM could be avoided. The second way is to use the entire surface of the DEM, instead of single points interpolated from it, as control for the aerial triangulation. This would reduce the error in height of the ground control points. Another way is to use GPS-supported aerial triangulation to decrease the dependency of the aerial triangulation on the quality of the selected ground height control points, thus increase the overall height accuracy of the whole block.

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