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Landslide's Mechanical Behaviour Study and Analysis Using Geodetic Observations

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1. Introduction

In this chapter, precise geodetic observations are used to detect and to evaluate the deformation of the Earth's surface in a local area with time. Soil deformations of very small magnitude can be evaluated and analysed.

Precise geodetic levelling is used to measure the elevation of a certain number of points carefully selected for their precision, location and repartition, before and after the deformation. Gross errors are eliminated by statistical analyses and by comparing the heights within local neighbourhoods.

In order to study the mechanical behaviour of the soil, it is considered as a mosaic of rigid blocks. Its mechanism is defined by the construction of the *"Characteristic Straight Line Method"* from precise geodetic observations.

This method is convenient and permits to evaluate a soil deformation of very small magnitude even when the displacement is of an infinitesimal quantity.

Geodetic levelling is a long-established technique used to measure elevation differences between successive bench marks and, by repeated surveys, to measure elevation changes (vertical displacements) as a function of time (Figure 1). Levelling has been used as a vertical geodetic measurement system long time ago, and has proved its utility at several metrological controls.

Repeated measurements of height enable measurement of the Earth's surface deformation over time. Such deformation can occur gradually, such as by land subsidence due to groundwater or soil withdrawal, or by sudden geologic events such as earthquakes or landslides. The direction and tilt of the vertical deformation caused by an earthquake or any other event could be deduced from the elevation of points measured before and after the event.

During geodetic levelling, a spirit level (or some other type of levelling instrument) and a pair of graduated levelling rods are used to measure the elevation differences between permanent bench marks by accumulating the elevation differences between a series of temporary turning points. The forward turning point (relative to the direction of the traverse) is called the foresight and the backward turning point is called the back sight (Allan, 1977)

Invar precision levelling staves are used in place of ordinary levelling staves. With parallel plate micrometers, readings up to 1/100000 of a meter can be taken accurately. The very high accuracy of precise levelling requires meticulous consideration of errors, which are theoretically predictable. A number of precautions must be taken while carrying out precision levelling. These are summarized as follows:

- The verticality of the staff must be ensured. Due to strong wind it is always difficult to hold the staff vertical due to which the observed readings are erroneous.
- Protection of the precise level from sun, wind, rain, etc... The sun causes a considerable trouble if it shines on the object glass.
- Lengths of the back and fore sights are kept within 50 meters or less.
- To avoid errors due to refraction caused by grazing rays, the levelling measurements must be carried out either in early morning or in late afternoons.
- The instrument must be adjusted before observations.
- Levelling of the instrument must be done carefully
- Earth's curvature and atmospheric refraction corrections must be performed

The use of the *"Characteristic Straight Line Method"*, developed here, can be considered as an innovation in topometric control process and gives to it additional extent as a monitoring tool of high accuracy.

The goals of the present chapter are as follows:

1. Describe and illustrate the utility of the *"Characteristic Straight Line Method"* in improving the accuracy of the topometric control for landslides monitoring
2. Evaluate what we can expect of vertical topometric observations in the field of any landslide monitoring program.

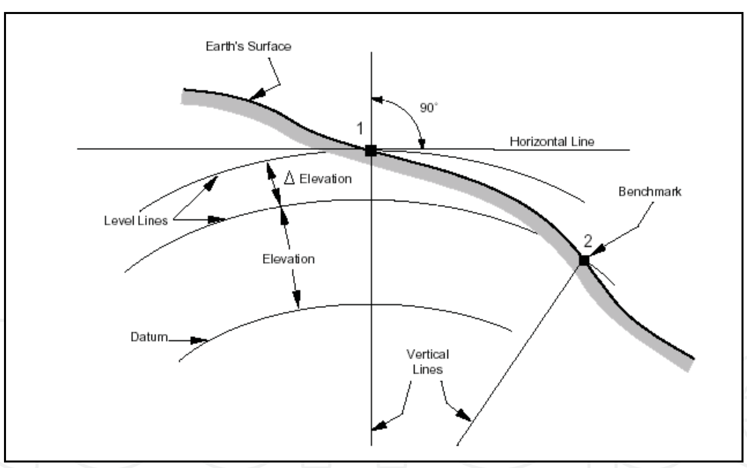

Fig. 1. Basic concept of topometric vertical control

2. Why not Space Geodesy

Space-based measurement systems, such as GPS (Global Positioning System) have put into the hands of the surveying community a powerful tool for the establishment of precise geodetic control surveys. Redundancy can provide proof of the precision to which a measurement is made. In order for this proof to be meaningful, the inclusion of possible error sources must not be systematically duplicated in the redundant measurements. Redundancy in a GPS survey is achieved primarily by way of a change in the relative geometry of the satellite constellation. This is easily visualized when one compares the dominance of the satellite geometry at a distance of 20,000 km. with the insignificant separation between typical project stations. For GPS surveys, the geometry of the satellite constellation must be different for repeat station observations in order to eliminate potential sources for systematic errors due to multipath, orbit bias, and unmodeled ionospheric and tropospheric delay. Even if the repeat station observation is made on another day, data must be collected at a different sidereal time in order to obtain a different satellite configuration.

Redundant observations also provide additional verification of centring error. Two unique situations regarding redundant GPS observations deserve comment. First, with the abundance of satellites visible at any given time and the availability of all-in-view GPS receivers, the possibility exists to compute quasi-independent vectors from the same observation session. A quasi-independent vector would use a different sub-group of four or more satellites during the same occupation. This technique is not considered valid fulfilment of the repeat station observation or repeat baseline requirements. Second, the pseudo-static technique by definition necessitates repeat station occupations. This paired observation is defined as one station observation for the purposes of these specifications. However, three station occupations could provide two independent baseline solutions, providing that the above-stated minimum sidereal time difference separates the first and third observations. For all other types of GPS surveying methodology, each station occupation can provide one station observation.

Each piece of equipment used during the survey to centre the antenna over the stations (tribrach, optical plummets, fixed-height rod, etc.) must be periodically tested, and if necessary, adjusted. The minimum test schedules are:

1. For accuracy bands less than 0.020 meters, each centring devise must be tested within 30 days prior to a survey commencement and within 10 days after completion of a survey.
2. For accuracy bands greater than 0.020 meters, each centring devise must be tested within 6 months prior to a survey's commencement and within 6 months after completion of a survey (Leick, 1993).

The duration of any GPS observation session is a greatly variable quantity depending on:

1. satellite associated errors (orbits, clock bias),
2. signal propagation errors (ionospheric/ tropospheric delay),
3. receiver associated errors (clock bias, antenna phase centre offsets/variations),
4. station associated errors (surroundings, centring, signal multipath and diffraction),
5. secondary effects (solid earth tides, ocean and atmospheric loading etc.),
6. uncertainties in alignment to reference frames.

GPS is 3D positioning method which determines coordinates in global geocentric orthogonal system *(WGS-84)*. From practical reasons the global coordinates X, Y, Z are transformed into ellipsoidal coordinates ϕ, λ, h and eventually into local horizontal coordinates n, e, u. Finally, the ellipsoidal heights are transformed to orthometric or (quasi)geoidal heights. For this step the knowledge of (quasi)geoid undulations N_i is necessary, which are defined by:

$$h_i = H_i + N_i$$

where h_i is ellipsoidal height, H_i is orthometric height, and N_i is geoidal undulation. The undulations can be determined in several ways using either absolute or relative methods. Geoidal surface is irregular and it is practically impossible to represent it by exact mathematical modeling function. Convenient is often an approximation through spherical harmonics expansion. Satellite (quasi)geoid can be modeled by a set of harmonic coefficients describing an Earth's gravity potential

$$W_0 = \frac{G \cdot M_E}{r} \left(1 + \sum_{n=2}^{n'} \left(\frac{a_e}{r}\right)^n \sum_{m=0}^{n} P_{nm}(\sin\varphi)\left(C_{nm} \cos m\lambda + S_{nm} \sin m\lambda\right) + \frac{\omega^2 r^2}{2} \cos^2\varphi\right.$$

from which the (quasi)geoid heights can be derived.

GPS height surveying is based on the determination of ellipsoidal heights, with subsequent reduction to given height system. It presumes application of an appropriate gravity field model which enables determination of (quasi)geoid undulations in respect to a conventional reference datum. The undulations must be determined in grid of sufficient density covering the survey area, and must be of sufficient quality, to allow for retaining of an appropriate height accuracy level.

Apart from global/regional networks, most of the practical GPS surveying applications are of extent of few kilometres, or tens of kilometres. In such cases is often used another procedure based on transformation with help of common points in both height systems (so called identical points). Appropriate types of transformations can be applied.

Precise geodetic levelling using methods such as the *"Characteristic Straight Line Method"*, offers several distinct advantages over GPS and other geodetic means. The most important advantage is the ability to determine near-absolute vertical displacement with respect to a reference outside the deformation area.

3. The Characteristic Straight Line Method

The *"Characteristic Straight Line Method"* is very easy to use. It improves the accuracy of the topometric vertical control in landslide monitoring. This method describs mathematical and statistical structure of a dynamic deformation model. This model includes very precise computations of displacements and displacements directions.

The *"Characteristic Straight Line Method"* can be described as follows:

Consider two points *A* and *B* of the rigid block. One assumes that the inclination of the rigid block is happened around a horizon axes passing through *A*. The bearing of the blocks inclination is θ_0.

The difference in altitude between the two ground points *A* and *B* is as follows:

$$h = H_B - H_A \ldots(1)$$

Where H_A is the altitude of point A and H_B is the altitude of point B

By differentiation:

$$dh = S dI \leftrightarrow \frac{dh}{S} = dI \ldots(2)$$

Where S is the horizontal distance AB, I is the inclination of the direction AB counted positive if B is above A, negative otherwise.

So, the ratio $\frac{dh}{S}$ is the variation of the inclination of the direction *AB* during the block movement.
The *dh* values can be obtained from levelling carried out before and after the Landslide.
On a convenient diagram, considered to be placed on a horizontal plane, one considers a point *O*, and a straight line *ON* indicating the north direction. To each couple of ground points *(A,B)*, one corresponds a point *(A,B)* of the diagram situated on a straight line oriented from *O* to *(A,B)* which bearing is θ (see Figure 1) at a distance from *O* equals in sign and magnitude the quantity $\frac{-S}{dh}$.

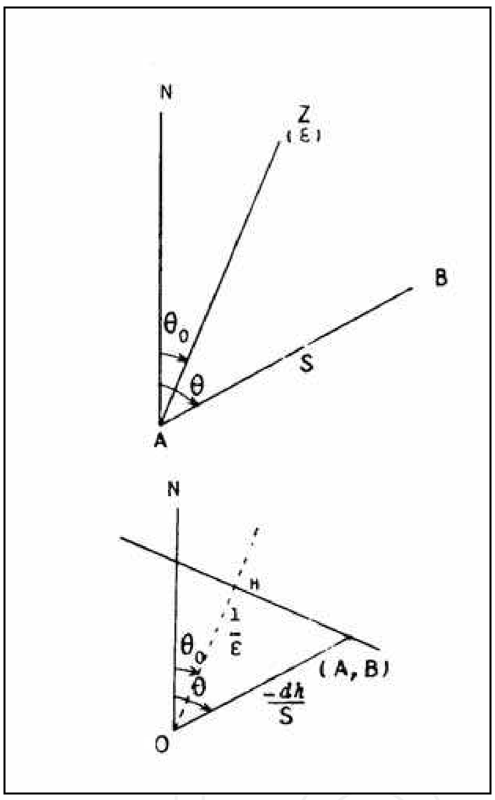

Fig. 2. The Characteristic Straight Line Method. The inclination of the block after the event is given by the inverse of the distance *OH*. The direction of the inclination *(θ_0)* is the bearing of the normal from *O* to the Characteristic Straight Line.

On the diagram, previously defined, one considers the straight line oriented *OZ* (Figure 1) which bearing is θ_0. In addition one considers H as the normal projection of the point *(A,B)* on this straight line.
So, in sign and magnitude we have:

$$OH = O(A,B)\cos(\theta - \theta_0) = \frac{-S}{dh}\cos(\theta - \theta_0) \cdots (3)$$

$$OH = +\frac{1}{\varepsilon} \cdots (4)$$

So, the point H is the same for any couple of points (A,B) of the rigid block.
In this way, all the points (A,B) on the diagram related to a same rigid block are aligned on the same straight line which we call the "*Characteristic Straight Line*" which could be constructed easily by using the quantities S and θ which one can obtain from a convenient map, and the altitude variation *dh* after the landslide's occurrence. This latest quantity is obtained by comparing the initial and the final vertical topometric observations.
The "*Characteristic Straight Line method*" seems to be more easy to use than the "*Characteristic Sinusoid Method*", but like it, this method provides immediately the characteristic parameters of the landslide dynamic: the direction and the tilt for each one the rigid blocks.
The dynamic of a rigid block is fully determined by using three ground points at least (non-aligned). The magnitude of the inclination ε equals the inverse of the distance OH, while the direction of the tilt is given by the bearing of the direction defined by OH.

4. Practical Validation of the *"Characteristic Straight Line Method".*

The "*Characteristic Straight Line method*" discussed here was tested by studying the landslide dynamic in an area located along the Amman- Jarash highway (Figure 3). The highway traverses an area of diverse geologic materials between Amman and Jarash (in Jordan). The rock units in the area have their characteristic weaknesses to weathering and erosion, ranging from chemical breakdown of some minerals in granitic rocks to weak shear zones that lead to instability of mountain-scale masses of rock. The types and abundance of landslides can be related to these characteristic weaknesses in the geologic units. The area has been the site of recurrent landslides and soil movement for more than 10 years. More exactly after the construction of Amman-Jarash highway.

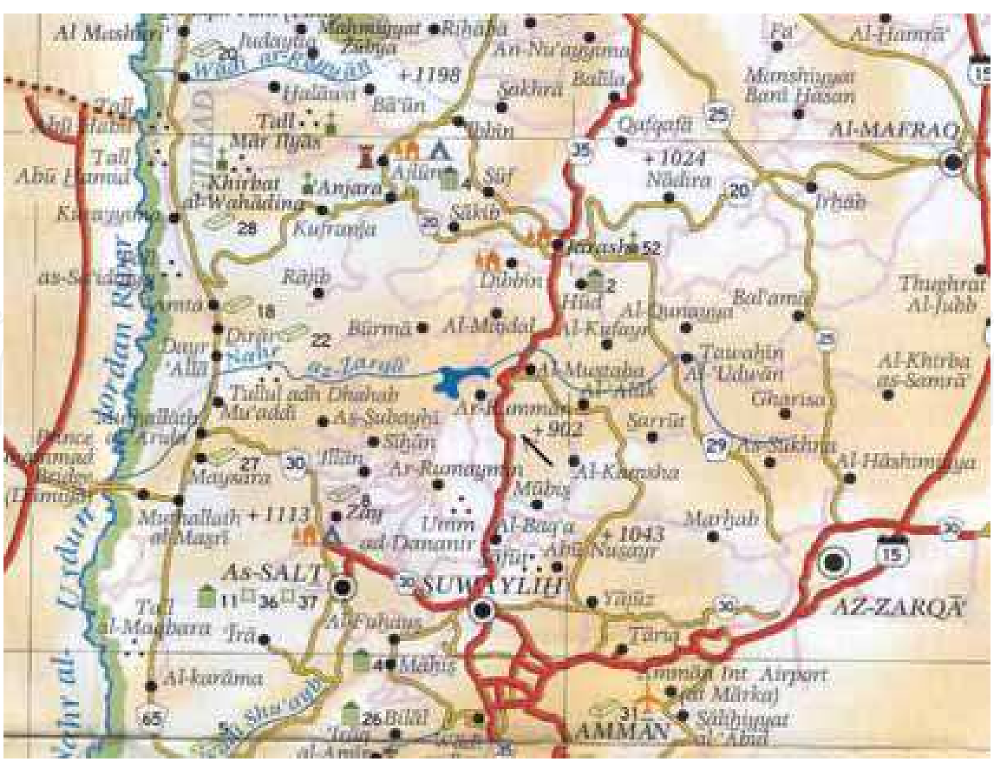

Fig. 3. The site of study (the arrow)

The deteriorating effects of landslides are well known. They usually cause soil damage and road blockage, resulting in major repair and maintenance costs. Economic losses can be significant to an entire region if a main route is closed for an extended period. Besides the costs associated with landslide damage, some types of landslides pose a risk to the safety of the travelling public. None of these risks can be eliminated. If roads are to pass through regions where landslides are common, the highway will be exposed to the risk of slide damage. The consequences of landslide movement are related to the size and location of a landslide, and the amount and velocity of soil movement. Larger slides may displace part of a roadway, resulting in greater repair costs. Larger displacements also translate to greater repair costs. If large movements accumulate slowly, over years or decades, they may be a continuing maintenance problem where cracks are filled and the pavement re-levelled frequently. Large, rapid displacements of even small volumes of material may undermine the road or deposit material on the road sufficient to close (or partially close) the roadway.

These smaller rapidly moving volume, slides are the most likely to pose a safety risk to the travelling public. Large and deep landslides are less likely to move rapidly or have significant displacement in any one episode of movement, but the rare rapid, large displacement of large landslides can have particularly severe consequences. Significant displacements of large and deep landslides may result in the roadway being closed for repair or, in the worst case, closed for long periods for reconstruction or rerouting. For the reasons mentioned above, it is primordial to study thoroughly these event and to determine with great precision their nature, types, sizes and the magnitudes of their displacements.

In order to study the soil movement in the area of study, all the rigid blocks (rocks) have been equipped with sufficient number of well defined ground points (at least 10 points per block). Complete levelling of the region occurred each summer and winter from 1997 to January 2008. The levelling surveys have been run to standards equal to those required for first-order, class 1 as set out by USA-based Federal Geodetic Control Committee (FGCC). The standard error for each elevation difference can be taken to be 0.5 mm. Levelling observations were corrected for rod scale and temperature, level collimation, and for atmospheric refraction and magnetic effects. Levelling surveys were not referenced to the national datum because we were only interested in monitoring relative elevation changes within the landslide region.

The "characteristic straight line method" has been used for each one of the rigid blocks by reporting on a diagram the points *(A,B)* defined by the values $\frac{-S}{dh}$ and the bearings θ previously defined.

Table 1 illustrates the soil deformation in the area of study during the investigation's period from 1997 to January 2008.

Looking through the values shown in Table 1, it is possible to estimate the dynamic of the landslide. The major part of the blocks are moving slightly in the same direction. Some blocks show more dynamic in the movement than others depending on their mass and on the neighbouring trough. For certain blocks, the height changes were not big enough; it can be concluded that the proposed "*Characteristic Straight Line Method*" gives the same results as the "*Characteristic Circle Method*". Both they could improve the accuracy of the precise vertical topometric control. It is clear that precise levelling based-on this method could be used for the study of the landslide dynamic of very small magnitude even when other means are insufficient for these purposes.

Bloc number	Bearing of the direction of tilt (in degrees)	Tilt magnitude (in degrees)
24	130° 30′ 55″	01° 12′ 34″
25	132° 54′ 52″	02° 31′ 00″
34	143° 10′ 12″	02° 01′ 32″
35	179° 35′ 16″	01° 52′ 21″
36	176° 22′ 45″	03° 21′ 43″
44	115° 55′ 14″	04° 50′ 52″
45	170° 44′ 47″	01° 40′ 41″
46	173° 14′ 23″	00° 53′ 23″
47	155° 00′ 51″	00° 31′ 21″
54	156° 37′ 54″	01° 11′ 55″
55	160° 11′ 01″	01° 50′ 12″
56	158° 36′ 11″	02° 32′ 16″
57	215° 26′ 56″	01° 00′ 02″

Table 1. Values of the magnitude and direction of the tilt of each rigid block. This illustrates the landslide dynamic in the region of AlJuaidieh (Amman-Jarash Highway) within the period 1997 – January 2008

Figure 4 shows the dynamic of the landslide in the area of study during the investigation period. By using topometric measurements elaborated before and after the events, and using field measurement of the bearings of the used ground points, a characteristic straight line has been constructed for each one of the moving blocks. The constructed diagram provides the blocks dynamics parameters: magnitude and orientation. From results illustrated in Figure 3 one can easily notice that very small soil movement could be precisely determined by using very simple techniques.

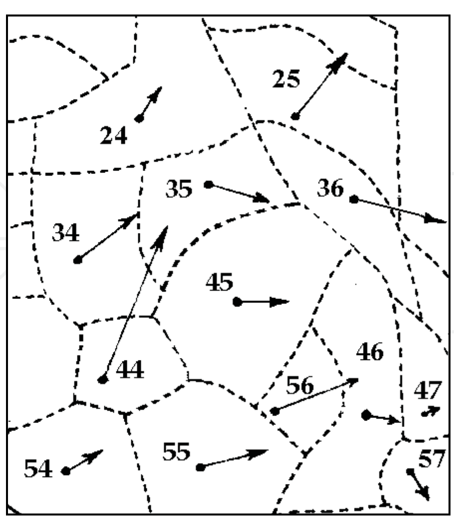

Fig. 4. Terrain deformation. Magnitude and direction of the tilt of the rigid blocs forming the moving terrain. Scale factor of the tilt magnitude is: 1cm = 1°. The planimetric scale factor is 1cm: 50m. The Directions of tilts are calculated with respect to the north direction (Table 1)

5. Conclusion

The most general movement of the soil after a landslide looks like the movement of a mosaic of blocks. The dynamic of each one can be fully described by: two rotations: the first, around a horizontal axis (inclination), and the second around a vertical axis (horizontal rotation), and two translations: the first is horizontal and the second is vertical.
The horizontal translations and rotations don't affect the altitudes. They, therefore, can't be predicted by levelling. In contrast, any inclination of the block modifies the relative altitudes of its points. So it can be detected by relative levelling interior to the block carried out before and after the movement.
It is clear that if one knows the inclination of a block and the variation in altitude of at least one of its points, it is possible to determine the variation in altitude of all its points so as the variation of the its mean altitude.
The "Characteristic Straight Line Method", discussed here, can be considered as an innovation of the topometric monitoring in the field of landslide dynamics study.
It could give the topometry a considerable extent to become a monitoring tool of very high accuracy. It permits the exploration and the accuracy improvement of these techniques. It permits to evaluate a soil deformation of very small magnitude even when the dynamic is of an infinitesimal quantity.
The results of a test using a very interesting area where an important landslide land occurs show the advantages of the proposed method in terrain deformation control and monitoring. The results obtained here are very close to these obtained by using the "Characteristic Circle Method" knowing that this method is more easy to use and the "Characteristic Straight Line Method" permits to construct the diagram without any difficulties.

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The techniques of computer modelling and simulation are increasingly important in many fields of science since they allow quantitative examination and evaluation of the most complex hypothesis. Furthermore, by taking advantage of the enormous amount of computational resources available on modern computers scientists are able to suggest scenarios and results that are more significant than ever. This book brings together recent work describing novel and advanced modelling and analysis techniques applied to many different research areas.