

Use of ArcMap for 3D Stability Analysis of Preexisting Landslides

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ABSTRACT

Different methods of stability analysis ranging from 2D simplified methods to 3D methods are used in the world. However, due to the time consumption and over estimation of factor of safety, 3D stability analysis has not been more widely used. In the preexisting landslides, 3D stability analysis is very important as all prevention measures are planned based on the safety factors. Although there is plenty of 2D stability analysis software, 3D stability analysis is very limited in number, and are very complex and time consuming. ArcGIS Spatial Analyst and ArcGIS 3D Analyst extensions were used to calculate the factor of safety (FS) of preexisting landslides. Simultaneous calculations were possible for both 2D and 3D analyses. Besides, it was possible to observe the results in the form of map and feedback the assumed parameters to get the best results, which is almost impossible in the available stability analysis software. This paper deals with the methodology of simultaneous 2D and 3D stability analyses using ArcGIS extensions for eight preexisting landslide blocks in Japan.

Key words: stability analysis, landslides, shear strength, sliding blocks, factor of safety

BACKGROUND

Landslide is a three dimensional phenomenon. However, 3D stability analysis is rarely done in the stability analysis of landslides. That is due to the availability of 2D software, requirement of less data and simplicity in the analysis method. Moreover, there is no agreement in the assignment of shear strength (c and ϕ) during stability analysis. Some neglects the value of c whereas the others either estimates it with respect to average depth or according to the linearly interpolated result of the shear envelope. Although Skempton (1985) mentioned to use the value of shear strength in between fully softened and residual values, residual shear strength are reached at large displacement in case of degradable soils such as mudstones (Tiwari and Marui, 2002). Therefore, it is necessary to test the soil samples from the landslides for the amount close to the displacement of the landslide block. Ota et al. (2001), Kimura et al. (2002), Hayashi et al. (2001) and other researchers explained much on the modified Hofland's method for 3D stability analysis. This paper modified the Hofland's method (1977) for the spatial distribution of shear strength, to make compatible to the available state of the practice GIS software. Xie et al. (2003) had mentioned the state of the

arts practice of GIS in slope stability and possibility of 3D stability analysis using arcObject. However, their paper was based on the simulation of critical failure surface for the slope with uniform ground surface. This paper further modified the Hofland's formula in order to use the arcMap for the stability analysis of simulated ellipsoidal sliding surface as well as actual landslides.

3D STABILITY ANALYSIS MODEL FOR GIS APPLICATION

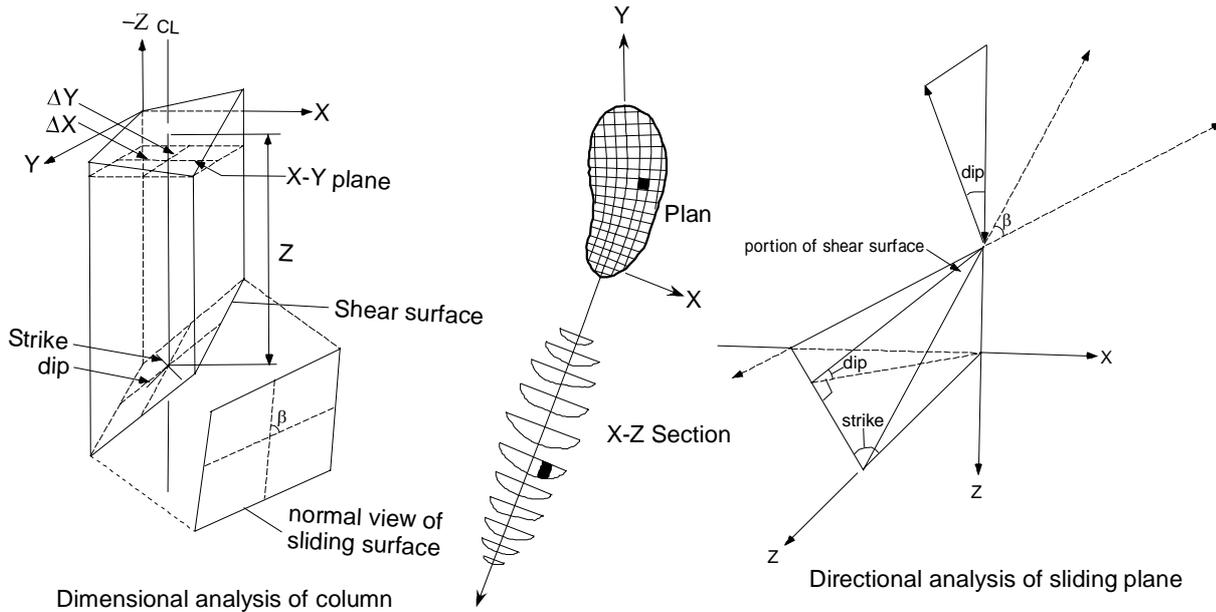


Fig. 1 Hofland's figure for the resolution of forces for the 3D stability analysis

Various methods of 2D stability analysis such as Fellenius method, Bishop's simplified method, Morgenstern and Price method, Spencer's method, Sharma's method, Janbu's method, Effective stress method and so on are available and various software based on fortran, basic, auto cad and simple excel spread sheet are available in the market for the stability analysis (Huang, 1983). Hofland (1977) proposed a new approach for the 3D stability analysis of landslides. Although various FEM methods and simplified methods of 3D analysis were proposed by Chen et al. (1983 and 2001), Hungr (1887) and others, Hofland's method is used in this analysis. Modification of Hofland's method (Fig. 1) has been done as follows.

$$FS = \frac{\sum_X \sum_Y \left(\frac{c \Delta X \Delta Y \sin \theta}{\cos \alpha_{xz} \cdot \cos \alpha_{yz}} \right) + \sum_X \sum_Y (\gamma \cdot Z \cdot \Delta X \cdot \Delta Y \cdot \cos(\text{dip}) \cdot \tan \phi)}{\sum_X \sum_Y \gamma \cdot Z \cdot \Delta X \cdot \Delta Y \cdot \sin \alpha_{yz}} \quad (1)$$

Modification of Hofland's formula can be done to cover pore water pressure as follows.

$$FS = \frac{\sum_X \sum_Y \left(\frac{c\Delta X\Delta Y\sin\theta}{\cos\alpha_{xz} \cdot \cos\alpha_{yz}} \right) + \sum_X \sum_Y \left(\gamma \cdot Z \cdot \Delta X \cdot \Delta Y \cdot \cos(dip) - \gamma w \cdot hw \cdot \frac{\Delta X \cdot \Delta Y \cdot \sin\theta}{\cos\alpha_{xz} \cdot \cos\alpha_{yz}} \right) \cdot \tan\phi}{\sum_X \sum_Y \gamma \cdot Z \cdot \Delta X \cdot \Delta Y \cdot \sin\alpha_{yz}} \quad (2)$$

In order to bring this formula to the compatible form to be used by GIS, the formula has been modified as follows.

Spatial analysis extension of ArcGIS 8.2 can be used to calculate the value of deepest slope of the sliding surface and orientation of that surface from north (aspect) automatically. The slope calculated by spatial analyst is exactly same as the value of 'dip', mentioned in Hofland's formula. However, Hofland mentioned the direction of Y-axis according to the direction of flow although he did not consider that in the equation. The direction of flow in the GIS based map for each zone in the landslide block can be estimated from the moving peg and inclinometer displacement data. That direction can be calculated as follows.

$$\Psi = (90 - (A - \Psi_0)) \quad (3)$$

where,

ψ : Strike mentioned by Hofland in degree

A: Aspect of the steepest sliding surface in degree

ψ_0 : Orientation of the displacement vector in degree

Statistical data on the analysis of many landslide blocks shows that value of ψ_0 is close to the value of the average aspect in most of the cases. Therefore, when the direction of the slide is not measured by regular monitoring, average aspect of the sliding surface can be taken as ψ_0 .

From the basic geometrics, we can derive,

$$\alpha_{yz} = A \tan(\sin\Psi \cdot \tan\beta) \quad (4)$$

$$\alpha_{xz} = A \tan(\cos\Psi \cdot \tan\beta) \quad (5)$$

$$\theta = A \cos(\sin\alpha_{yz} \cdot \sin\alpha_{xz}) \quad (6)$$

where, β : steepest slope of the sliding surface (dip in Hofland's equation and slope in GIS)

Now, the Hofland's equation has been modifies as,

$$FS = \frac{\sum_X \sum_Y \left(\frac{c\Delta X\Delta Y\sin\theta}{\cos\alpha_{xz} \cdot \cos\alpha_{yz}} \right) + \sum_X \sum_Y \left(\gamma \cdot Z \cdot \Delta X \cdot \Delta Y \cdot \cos(\beta) - \gamma w \cdot hw \cdot \frac{\Delta X \cdot \Delta Y \cdot \sin\theta}{\cos\alpha_{xz} \cdot \cos\alpha_{yz}} \right) \cdot \tan\phi}{\sum_X \sum_Y \gamma \cdot Z \cdot \Delta X \cdot \Delta Y \cdot \sin\alpha_{yz}} \quad (7)$$

The main benefit of ArcGIS tools is that we can divide the whole landslide area into a number of very small cell size, as small as few centimeter size as per the desire and necessity of the

analysis. Besides, equal value of ΔX and ΔY can be set. Now, equation (7) can be reduced into the following equation.

$$FS = \frac{\sum_x \sum_y \left(\frac{c \cdot \sin\theta}{\cos\alpha_{xz} \cdot \cos\alpha_{yz}} \right) + \sum_x \sum_y \left(\gamma \cdot Z \cdot \cos(\beta) - \gamma_w \cdot h_w \cdot \frac{\sin\theta}{\cos\alpha_{xz} \cdot \cos\alpha_{yz}} \right) \cdot \tan\phi}{\sum_x \sum_y \gamma \cdot Z \cdot \sin\alpha_{yz}} \quad (8)$$

which can again be simplified to

$$FS = \frac{\sum_x \sum_y A + \sum_x \sum_y B}{\sum_x \sum_y C} \quad (9)$$

$$\text{where, } A = \frac{c \cdot \sin\theta}{\cos\alpha_{xz} \cdot \cos\alpha_{yz}} \quad B = \left(\gamma \cdot Z \cdot \cos(\beta) - \gamma_w \cdot h_w \cdot \frac{\sin\theta}{\cos\alpha_{xz} \cdot \cos\alpha_{yz}} \right) \cdot \tan\phi \quad \text{and } C = \gamma \cdot Z \cdot \sin\alpha_{yz} \quad (10)$$

All components for the individual cylinders can be calculated by raster calculations using the above mentioned formula. Here, orientation of the average displacement direction of moving posts or the average aspect can be considered as Y-axis. In case where the direction of movement of the block is curved, separate axes are to be considered for each portions and analysis are to be done for each zone. In the analysis, marginal friction mentioned by Ota et al (2001) can also be considered for the boundary elements. ArcGIS Spatial Analyst can be used efficiently to calculate the value of FS for the whole block using equations 9 and 10 as explained below. Besides, FS at the mid section and at right quarter and left quarter could also be calculated automatically by summing up, using the zonal statistics function of the ArcGIS spatial analyst, for one meter strip at the corresponding locations.

Fig. 2 shows the schematic diagram for the calculation of FS. Main input parameters such as ground level are provided from digitized contour maps or the readymade DEM. Geological profile is input through the underground boring data. In the absence of sufficient boring data, ellipsoidal interpolation for each geological layer can be done. Ground water table can be prepared based on the ground level and the piezometer data. Boundary of the landslides can be obtained from the distribution of the cracks, monitoring data and the landslide topography. As 2D FS calculations are based on the 1m width strip in the middle of the slide, elongated polygon vector with 1m width at the mid and quarter sections can be input as the boundary for 2D FS. With the help of TIN of all the vector layers (features), made from 3D analyst extension, all input vector data are to be converted into the raster data. It is to be noted that the simple raster-vector conversion leads other undesirable layer. Value of c , ϕ and γ are set according to the type of rock (after conducting the shear test on the soil samples) and the field investigation. Average γ of the slice column can be calculated with the weightage of the depth of the rock types and γ for those rocks.

PROCEDURE OF SIMULTANEOUS 3D AND 2D STABILITY ANALYSIS

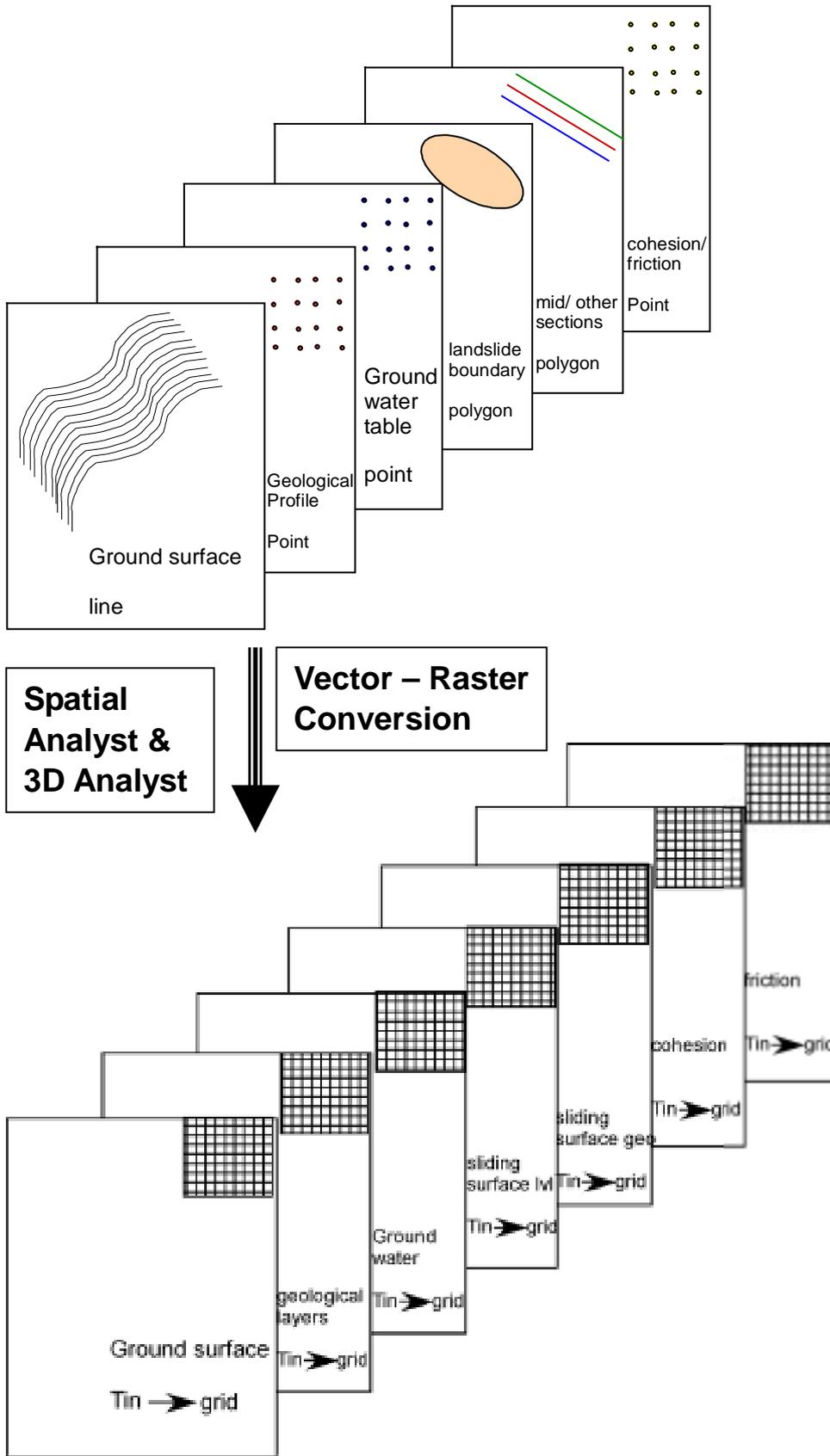


Fig. 2a Schematic diagram of Input vectors and conversion into raster data by ArcGIS

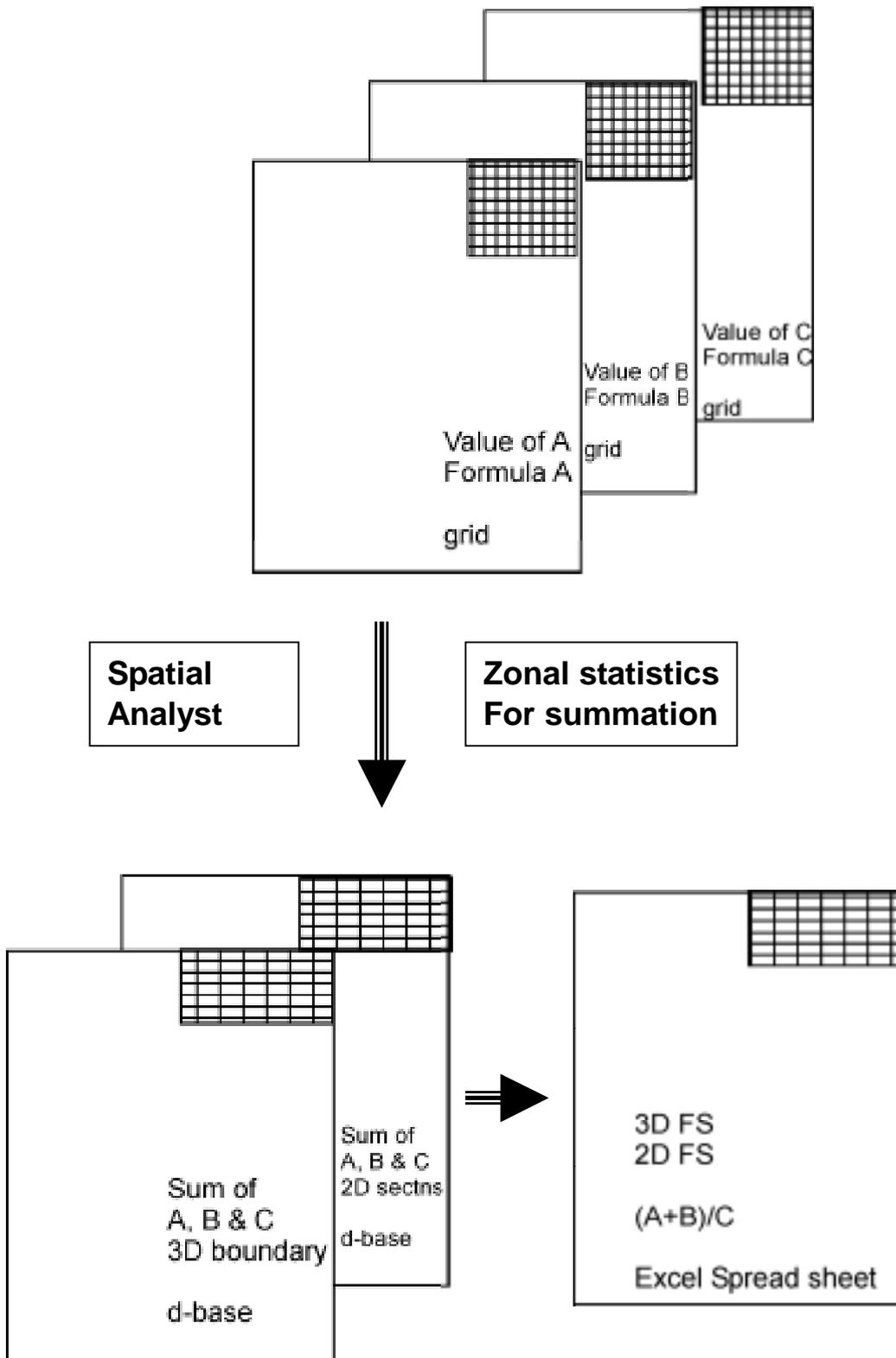


Fig. 2b Schematic diagram for the automated calculation for the 3D & 2D FS

CASE STUDY OF SIMULATED AND ACTUAL LANDSLIDE BLOCKS USING THE PROPOSED METHOD

Stability analysis of a simulated ellipsoidal landslide and eight actual landslide blocks were done to observe the applicability of the possible methods, which are described below.

A. Simulated ellipsoidal landslide

A uniform homogeneous slope with 80m length, 40m width and 6m depth has been considered for the simulation study. Variation in 3D and 2D FS was calculated in this block in order to see the applicability of the method in a symmetrical section. The same block was analyzed by the state of the art technique and the result was compared with the GIS based results. For automatic calculation of the coordinates, data base of the coordinates with 25cm cell size was prepared by simple mathematical programming with the following equation.

$$\frac{x^2}{40^2} + \frac{y^2}{20^2} + \frac{z^2}{6^2} = 1 \quad (11)$$

The horizontal ellipsoidal, made in this way was transformed to the actual slope of the landslide by data transformation. Value of 3D and 2D FS were automatically calculated with the procedure explained above. The result of the geometry of the sliding block and the FS calculation is shown in Table 1 and 2 respectively. Average longitudinal and lateral slope as well as average value of c and ϕ is shown in Table 2.

B. Actual Landslide Areas

Eight different landslide areas in Niigata Prefecture, Japan with varying geometry and sliding characteristics were considered for the study (Fig 1): Okimi (3 blocks), Yosio, Mukohidehara (2 blocks), Iwagami and Tsuboyama were the studied landslides. Total 38 soil samples were collected from the main and side scarps as well as sliding zones of those landslides in order to measure the values of c , ϕ and γ . Okimi landslide, which has long history of monitoring and investigations with a number of countermeasures was considered as the major analysis area. Total 18 soil samples were collected from Okimi landslide. Okimi, Tsuboyama and Mukohidehara were triggered along the Sugawa formation whereas other two landslides were triggered along Taruda formations. Both formations had mudstone as the dominating rock type. It is to be noted that almost 70% of the total landslides in Niigata Prefecture are supposed to be induced along mudstone formations.

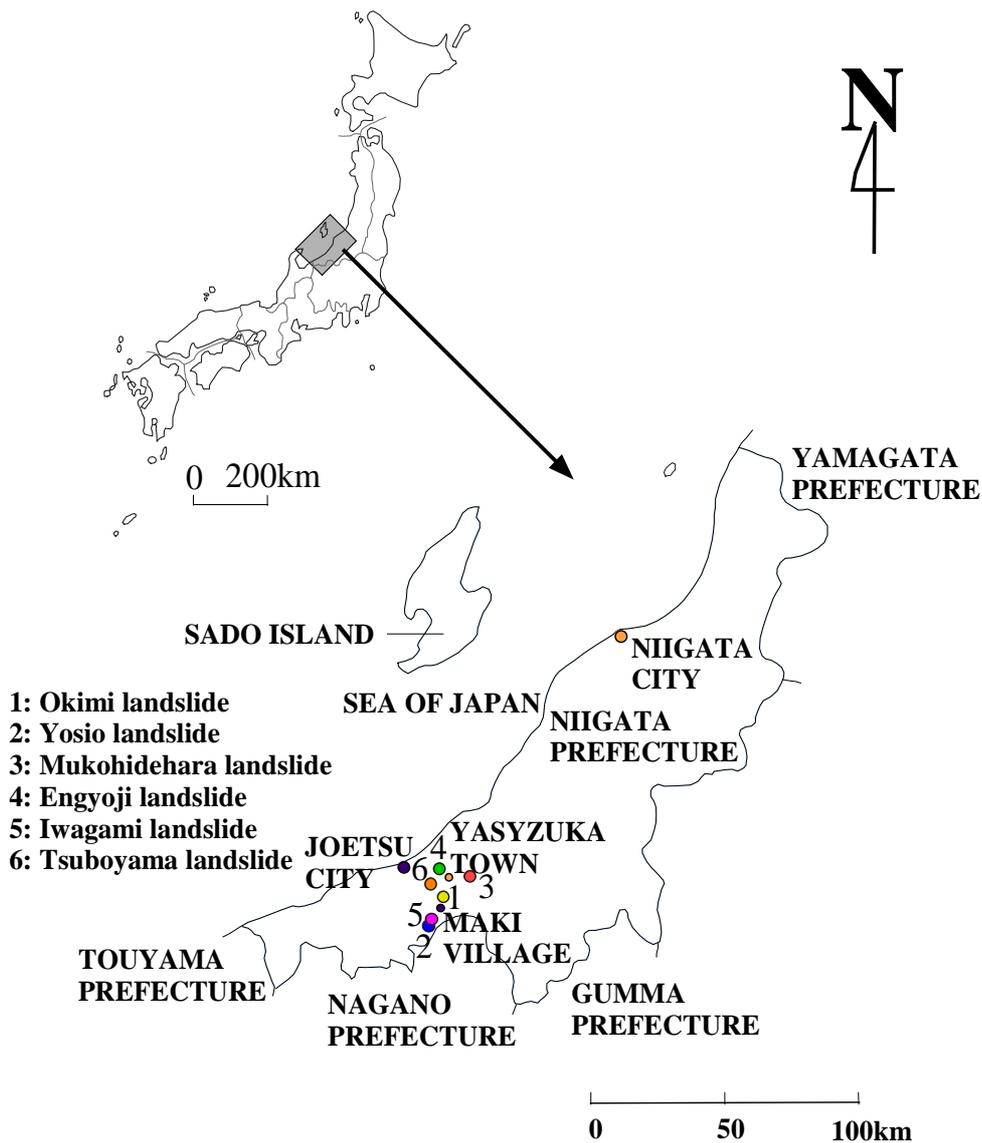


Fig. 3 Location map of the studied landslide areas in Niigata Prefecture, Japan

Table 1 Geometrical configuration of the studied landslide blocks

Landslide area	length in plan, m	variation in width, m	average depth, m	L/Dav	L/Wav	Wav/Dav
Ellipsoidal block	80	10-40	4	20.00	2.67	7.50
Okimi, A block	770	170-260	11.5	66.96	3.58	18.70
Okimi, C block	680	160-400	11.9	57.14	1.94	29.41
Okimi, D block	710	160-300	9	78.89	2.54	31.11
Yosio	225	60	6	37.50	3.75	10.00
Iwagami	140	90	12	11.67	1.56	7.50
Mukohidehara C4	175	50-75	12	14.58	2.92	5.00
Mukohidehara G5	90	30-40	8.5	10.59	2.57	4.12
Tsuboyama	215	35-55	10	21.50	4.78	4.50

Table 2 Slope of the landslide blocks and average value of shear strength used in the analysis

Landslide area	c, kPa	ϕ , degree	long. Slope, %	Trans. Slope, %	Tilt direction
Ellipsoidal block	5	13	50	0.00	horizontal
Okimi, A block	5	11.8	14.2	5.5	left
Okimi, C block	7	16	17.9	6.9	left
Okimi, D block	5	11.8	14.1	3.6	left
Yosio	8	10	14.3	6.3	left
Iwagami	6	12.3	28.6	9.1	left
Mukohidehara C4	12	12	21.6	12.8	left
Mukohidehara G5	12	10	27.4	25	left
Tsuboyama	6	9.5	18.18	6.00	left

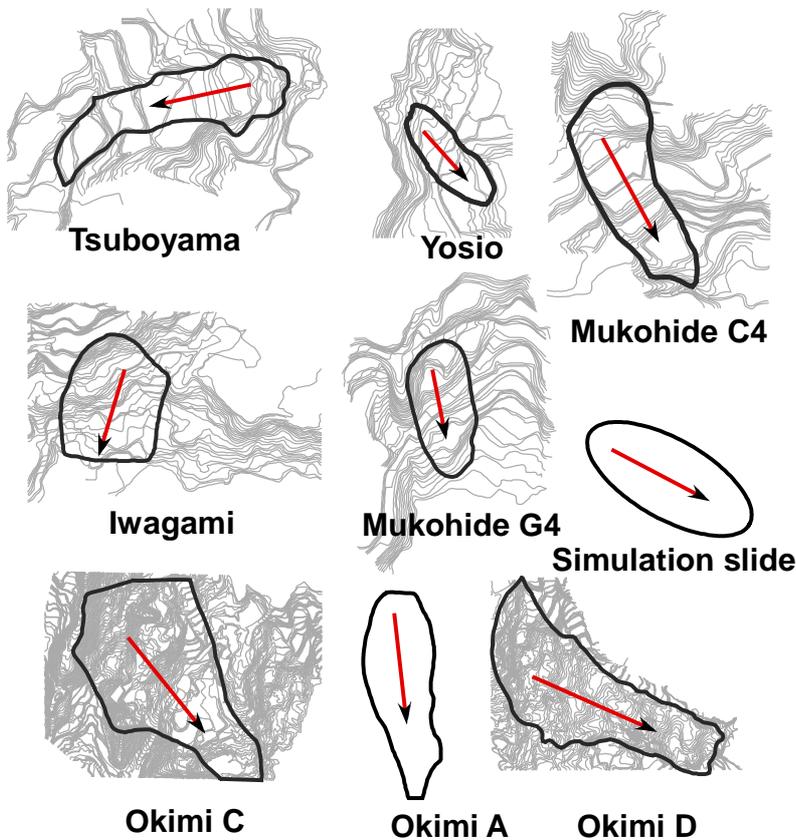


Fig. 4 Geometrical configuration of the analyzed landslide blocks

Table 3 Calculated values of the FS using proposed methodology

Landslide area	3D FS	2D FS mid	2D FS left	2D FS right	2Dav/3D	2Dmid/3D
Ellipsoidal block	1.01	0.95	1.03	1.03	0.99	0.94
Okimi, A block	0.96	0.85	0.79	1.31	1.02	0.89
Okimi, C block	1.14	0.93	0.72	1.82	1.01	0.82
Okimi, D block	1.01	0.89	0.83	0.92	0.87	0.88
Yosio	1.14	0.99	0.92	1.79	1.08	0.87
Iwagami	0.75	0.76	0.91	0.54	0.98	1.01
Mukohidehara C4	0.97	0.91	0.62	1.09	0.90	0.94
Mukohidehara G5	0.99	0.9	0.94	0.66	0.84	0.91
Tsuboyama	1.03	0.91	0.83	1.06	0.91	0.88

Test Findings and Stability Analysis results

The soil test results for residual shear strength are shown in Table 2. In the places where displacements are less than that required for residual stage, shear strength at that displacement has been considered. Value of 2D and 3D FS for the major blocks (as mentioned in the annual reports) of the landslide area are shown in Table 3. However, detailed analysis of the movement data is helpful to divide the further blocks within the proposed major blocks. The test result of 2D stability analysis shows that there is variation in FS based on the section. Contour maps and the bore log result of all the landslide areas were taken from the annual reports of those landslides, available in the office of Niigata Prefectural Government. In case of A block of Okimi landslide, there were more than 70 boring points. Therefore, FS was calculated not only with high confidence, but also for various small sliding blocks, such as upper half portion, right half portion, left half portion and so on. Plan of those landslides are shown in Fig. 3 and the geometry of the landslide and calculated FS values are shown in Table 2 and 3 respectively. Slope and average shear strength parameters, obtained from ring shear test results for the displacement close to the actual displacement of the landslides are shown in Table 2.

Whole landslide areas were digitized and TIN of the whole blocks were made using Arc GIS spatial analysis and 3D analysis tools. Results of the underground geological information and ground water tables mentioned in bore log were added at spatially distributed boring locations. The sliding surfaces at various levels: shallowest sliding surface with the colluvium material and the deepest sliding surface at the contact of weathered and intact mudstone were made automatically using 3D analyst and Spatial analyst simultaneously. Besides, ground water profile was based on the piezometer data and the ground profile. Based on the sliding surface and ground water profile at the cross-sections along various drilled locations, tentative profile of the variation in the sliding surface and the ground water at X-Z axis was made. These profiles were transferred throughout the Y-axis where there are no boring points. The main advantage of the Arc GIS was that the sliding surface and ground water tables could be observed in 3D as well as at all sections. That makes the estimations of those profiles more closer and smoother. The whole landslide areas can be divided into very small grids (about 0.2m) and stability of each cylinder can be checked with modified Hofland's formula as explained above.

DISCUSSION ON THE ANALYSIS RESULT

From the stability analysis results, it is clear that 3D stability analysis gives relatively higher

value of FS compared to that of mid-section. Duncan (1996) mentioned that 3D FS is about 10% higher than the 2D FS. Duncan's postulation was close in case of ideal (ellipsoidal) sliding surface. Most of the state of the art analysis are based on the critical failure surface estimation and are developed for the uniform topography. However, actual sliding surface of the landslide is rather complex and general postulations cannot be done for the 3D sliding surface. This differs in the value of FS at various sections. For example, in Okimi landslide, the originally estimated blocks can be divided into small blocks according to the displacement data and the stability analysis results. It is not necessary that mid-section always give least FS. Section with minimum FS depends on the location of the sliding surface, geometry of the 3D sliding block, slope and the nature of the ground surface and direction of the movement. However, if the sliding direction and slope of the sliding surface is relatively uniform (with average width, maximum width ratio close to unity) and more or less horizontal transverse slope, the mid-section gives least FS compared to other sections. Higher value of 3D FS in all the cases is due to the resolution of all the forces to the sliding direction.

The main benefit of ArcGIS in stability analysis is that stability of the shallowest and deepest sliding surface can be done at the same time automatically, based on the same map. It may take time to prepare the input data set in the beginning. However, the analysis and the calculations based on the ArcGIS tools are very fast as well as multi-dimensional once those input data sets are prepared.

CONCLUDING REMARKS

From present study, it is understood that ArcGIS tools can be used as one of the most appropriate software for 3D stability analysis of pre-existing landslides. ArcMap, in combination with Spatial Analyst and 3D Analyst extensions are far better than the state of the art 2D analysis software for the analysis of the landslides as all the data and the analysis results can be viewed in three dimension and corrections/modifications on the geometry of various parameters can be done simultaneously. ArcMap analysis tools might be expensive in the beginning compared to the other software. However, the possibility of its multi dimensional use for various purposes of the landslide analysis can make it very reasonable compared to other analysis software.

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