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APPLICATION OF PFC^{3D} FOR SLOPE MOVEMENT ON COLLUVIAL SOIL

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Abstract

In the mountainous area of the tropics, soil creep often occurs on residual soil and colluvial deposit. The rate of this phenomenon varies from very slow to extremely slow and is difficult to detect without equipment as well as model. Within PFC^{3D} (Particle Flow Code in three dimensions) granular materials such as soils are simulated by balls. And the PFC^{3D} model was applied for colluvial soil creep. Although existing of some limitations, this application determined direction of creeping as well as zone of creeping of culluvial soil.

Keywords: *Creeping, colluvial soil, balls, PFC^{3D} model*

1 Introduction

Kalibawang Irrigation Channel has been found to be threatened by landslide risk in every rainy season. Among many types of slope movement ever found, slope creeping is the most devastating hazard to the infrastructures and the private properties. In the case of slope at Km 15.9 which is located in Mejing village of Kulon Progo Regency, Yogyakarta Special Province, the continuously slow slope movement is suspected to induce additional stress on the bridge and the channel bridge downhill to deform in every rainy season. In response to such serious problems and toward the development of sustainable slope protection, a collaborative research project "Development of sustainable slope protection in tropical residual soils" under the support of JICA and the Directorate General of Higher Education, Indonesia has been initiated. A branch research of this project aims to determine the mechanism of creeping by using a monitoring system (including 3 piezometers, 5 extensometers, 25 strain gauges, 3 soil moisture gauges, and 1 rainfall recorder) to develop the model for slope movement. And this application was considered the first application of PFC^{3D} model for colluvial soil movement in Indonesia.

2 Site Characteristics

2.1 Location

Based on the relative benchmark system, the study area is located at Km 15.9 Kalibawang Irrigation Channel, about 20km in the western part of Yogyakarta Special Province of Central Java Island, Indonesia. It lies on a gentle slope with the dip angle ranging within 10-15 degree and has the co-ordinates of X: 411700–411900, Y: 9145500–9145700 with Universal Transverse Mercator (UTM) Zone 49 Southern Hemisphere (Figure 1).

2.2 Geology

The slope at Km 15.9 Kalibawang irrigation channel is mostly covered by colluvial deposits consisting of andesitic breccia intercalated with soft tuffaceous clay and underlain by mudstone belong to the Nanggulan formation (Figure 2). These clay layers are suspected to be rich in

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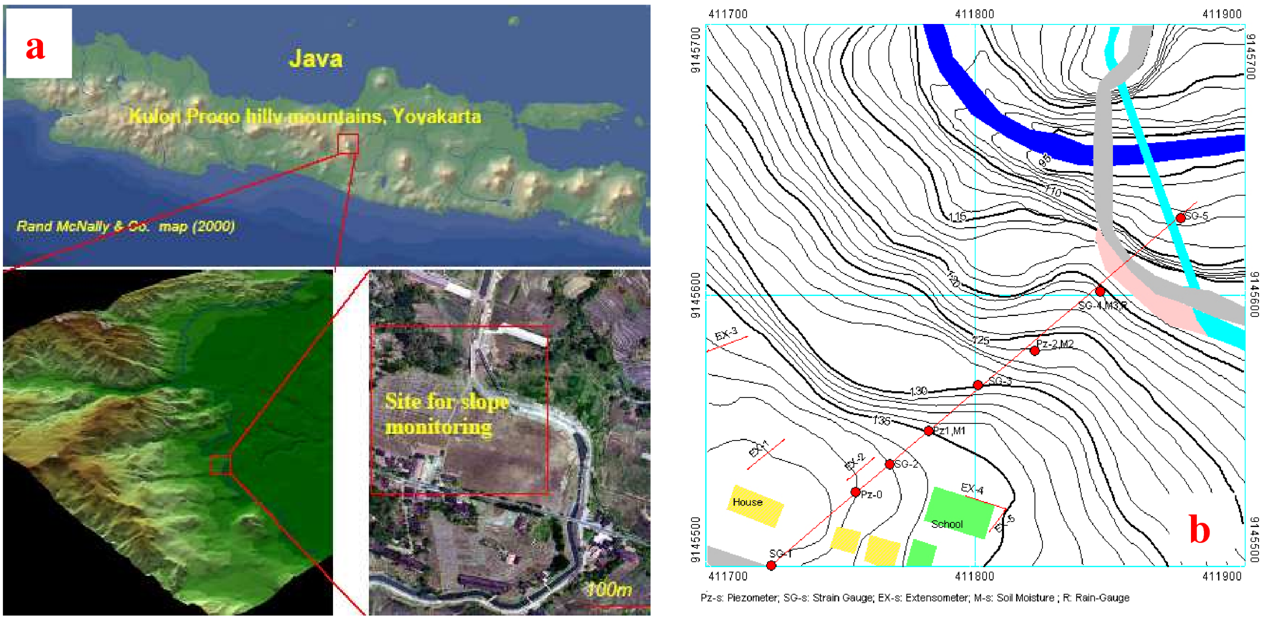

Figure 1: The study area (a) and monitoring system line (b).

montmorillonite clay mineral which is susceptible to swell and shrink when in contact with water. In addition, with distinctive properties in terms of strength and permeability from the surrounding slope material, these clays may trigger the instability of the slope.

2.3 The Cross-section

The cross-section from SG-1 to SG-5 (Figure 2) was made based on the drilling log result, the soil properties result, SPT N-value result as well as the result of geoelectrical analysis. A total of 9 layers have been identified and the summary of the geotechnical properties of each layer is shown in Table 1.

2.4 The Slope Monitoring Result by Using Strain Gause

Five pipe strain gages (SG-1 to SG-5) were inserted into five of the eight boreholes mentioned earlier in order to detect the sub-surface movement (slip surface) starting from the crest of slope until its toe. Since only 25 gages were available for this site, the amount in each pipe strain gauge (each borehole) varied depending on the complexity of the lithology found during drilling and the expected results to be achieved.

Results show that the movement of colluvial slope is very complex. It has been found that some movements have occurred not only at the contact between the colluvial deposit and the base of mudstone, but also at the zone above ground water table. The movements at the contact between colluvial deposit and mudstone may have been induced by pore-water pressure in response to the fluctuations in ground water level (increasing or losing pore-water pressure) or perhaps caused by the capillary rise or suction loss in response to the wetting of soil by rain infiltration. Meanwhile, creeping occurred dominantly in the contact between the mudstone layer and tuffaceous medium sandstone as well as tuffaceous fine sandstone, although the tuffaceous fine sandstone had a high SPT value. Moreover, all of the recorded movements were noticed to be not only relatively parallel to the slope dip direction but also followed different trends.

The results also illustrate that the strain value of shallow movements were bigger than that of deeper movements, Figure 3.

3 The Limitation of Problem and Model

One of limitations of PFC^{3D} program is the limited number of distinct elements (balls) which

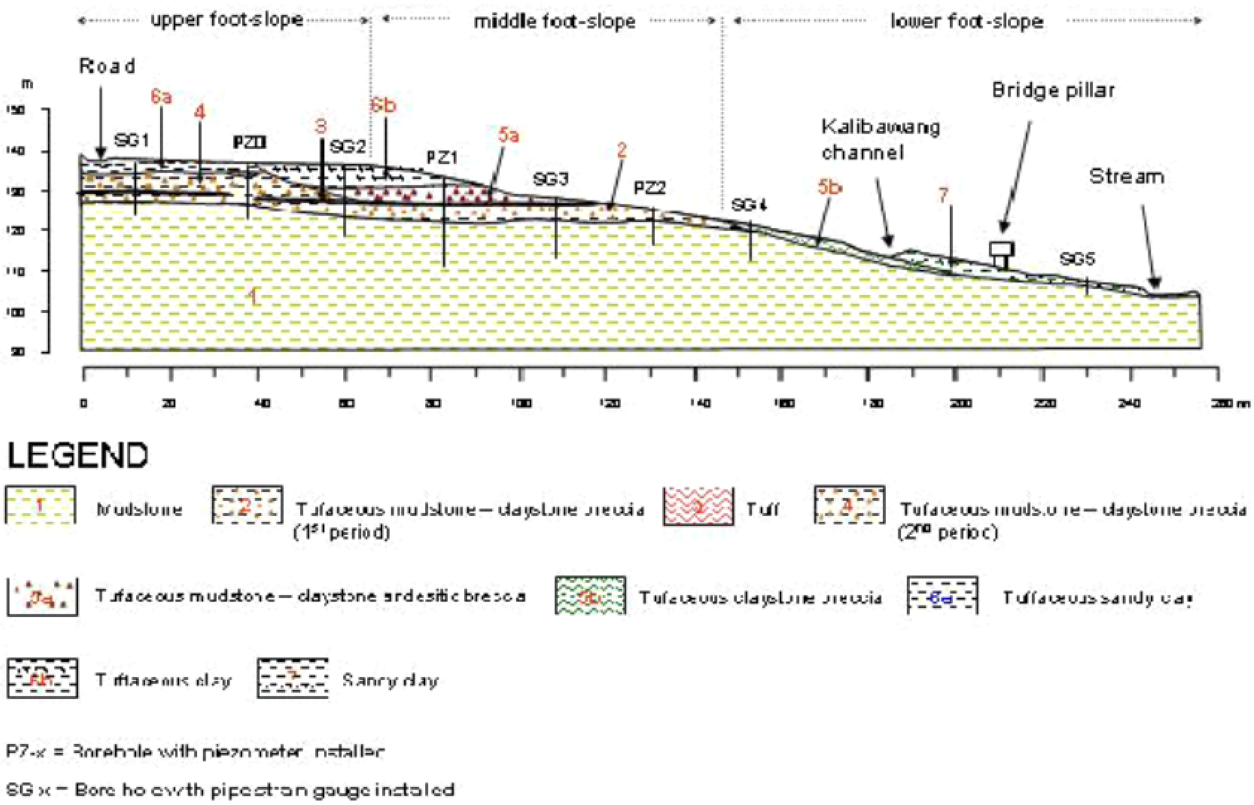

Figure 2: Cross-section of the Kalibawang Channel arround km 15.9 (Karnawati, 2005).

Table 1: Summary of laboratory test results (Civil Engineering Dept, UGM in 2005.

Layer ID	Layer name	Specific gravity G_s	Bulk Density g/cm³	Dry Density g/cm³	Strength parameter		N Value
					□°	C (kN/m²)	
1(6a)	Tuffaceous Sandy Clay	2.76	1.55	0.98	5.54	33.6	18-21
2(6b)	Tuffaceous Clay	2.69	1.52	0.98	35.54	11.00	7-17
3(4)	Tuffaceous Mudstone-claystone breccia (2nd period)	2.72	1.60	1.05	14.24	83.90	25-40
4(5a)	Tuffaceous Mudstone-andesitic breccia	2.58	1.60	1.07	18.22	56.87	25-40
5(3)	Tuff	2.72	1.63	1.06	5.37	31.70	24-41
6(2)	Tuffaceous Mudstone-claystone breccia (1st period)	2.64	1.59	1.00	37.1	12.00	27-60
7(5b)	Tuffaceous claystone breccia	2.62	1.61	1.09	21.82	24.04	35-45
8(7)	Sandy clay	2.63	1.58	1.07	25.74	34.00	25-25
9(1)	Mudstone	2.75	1.68	1.26	17.62	40.80	46-65

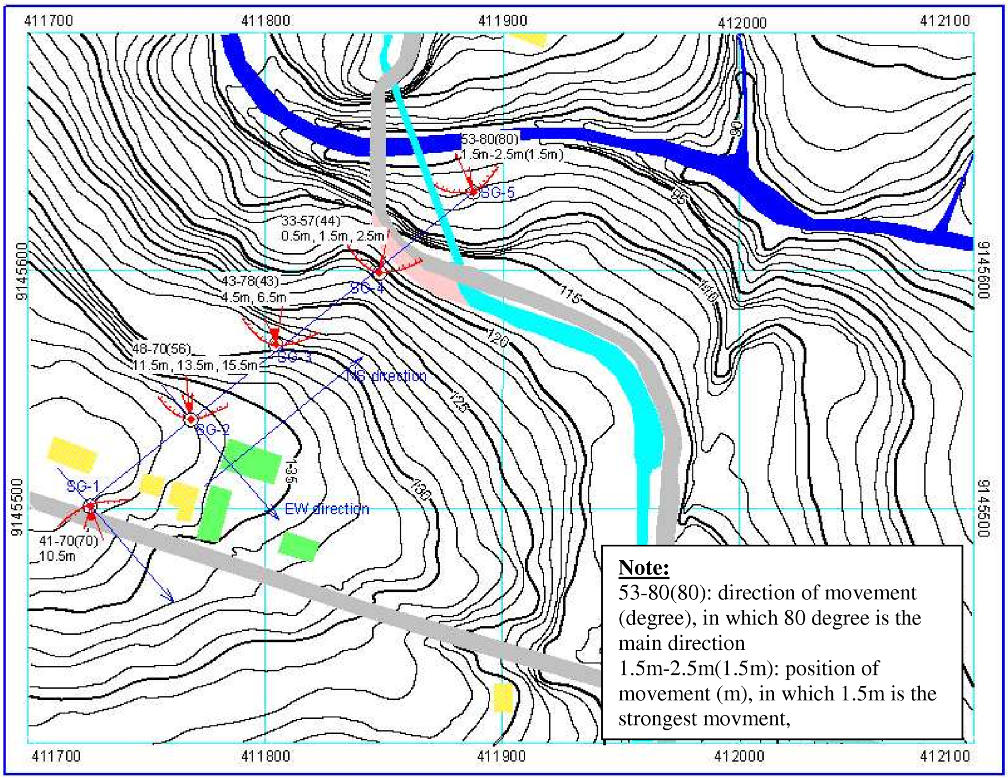

Figure 3: Monitoring result of direction and positions of all movement.

are created and controlled by computer during simulation, and require a bigger area to be chosen for better result. The 3D model consists of scope monitoring area with 40m of height including the channel bank as well as the bridge and stream.

After trying with some cases, a final box which is 260 m long, 200 m wide and 40 m high is chosen for PFC^{3D} model. The study area is bounded by coordinates X: 411700–411960 and Y: 9145450–9145650 as shown in Figure 4.

The 3D model is 2.080.000 m^3 (2.08 km^3) in cubic while requirement of number balls of PFC^{3D} is limited. After trying with 90.000 balls, 75.000 balls, 60.000 balls, 45.000 balls and 30.000 balls, the results revealed that the computer (3 GHz of P-IV CPU, 1G of RAM and 200 GB of HDD) only runs well with balls ranging 30.000–45.000.

In this research, the balls in PFC^{3D} model were assumed as soil particles and were having the properties of soil particles (the micro properties for each layer are calibrated prior to the simulation by using biaxial test. The association between the PFC synthetic material and a particular physical material is established by the simulated material testing). Thus, the balls which were presented the mudstone-sandstone particles in basement layer (mudstone-sandstone layer) could be moved by laws using in PFC^{3D} model.

4 Simulation and Discussion

First, 2080 cells (5m $\times$ 5m) are created in correlation to the 52.000 m^2 as shown in Figure 4. The Visual Basic program is used to create the 3D grid point. Total 54.203 points are created and the ID_layers of every point are set based on the boreholes and the cross-section (according to the standards of Geological Engineering). The surface of 3D grid point is shown in Figure 5.

Second, 30.000 balls with distribution radius of 1.5-3.5m are created randomly within the box 260 m $\times$ 200 m $\times$ 80 m, then the balls are dropped and auto arranged by gravity. After reaching a steady state condition, the logical

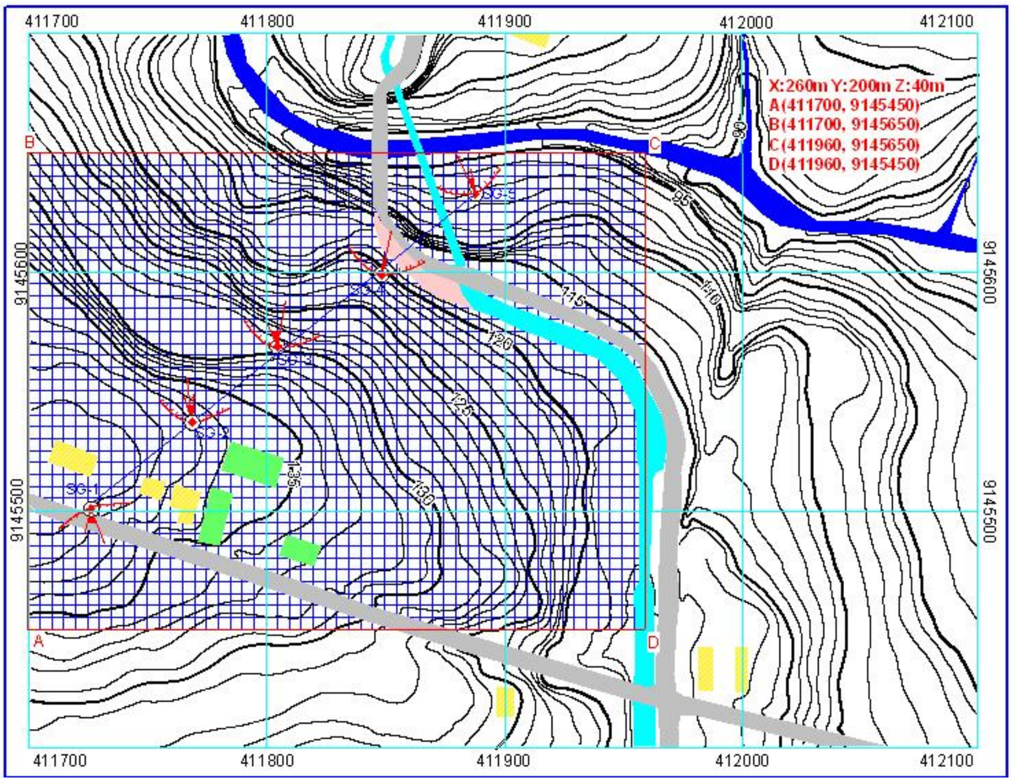

Figure 4: The chosen area with 2080 cells for setting 3D grid point.

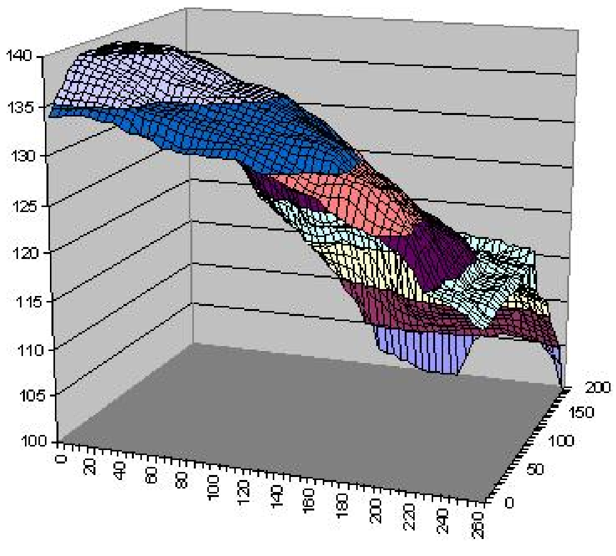

Figure 5: The surface of 3D grid point.

balls are chosen to build the model by using the Visual Basic program. The final model consists of 16.295 balls which are set in 9 layers, (Figure 6). The input parameters of each layer are shown in Table 2.

The model is considered to be in equilibrium when the maximum (or average) unbalanced force is small compared to the maximum (or average) contact force in the model for a packed assembly of particles. According to the 10^{-5} ratio set, the simulation stopped at step 16.998 (Figures 7 and 8).

During this simulation, the maximum unbalanced force fluctuates around 3.000-7.000 kN in the first 2.000 steps and around 400-2.500 kN from step 2.000 to step 8.500, after that, it decreases gradually from step 8.500 to end. Meanwhile, the average unbalanced force decreases gradually at the beginning to the end of simulation (Table 3 and Figure 9). The vector of displacement of balls show that the balls creep as flow following some directions, and all big displacements occurred dominantly at the right side of model, (Figure 10).

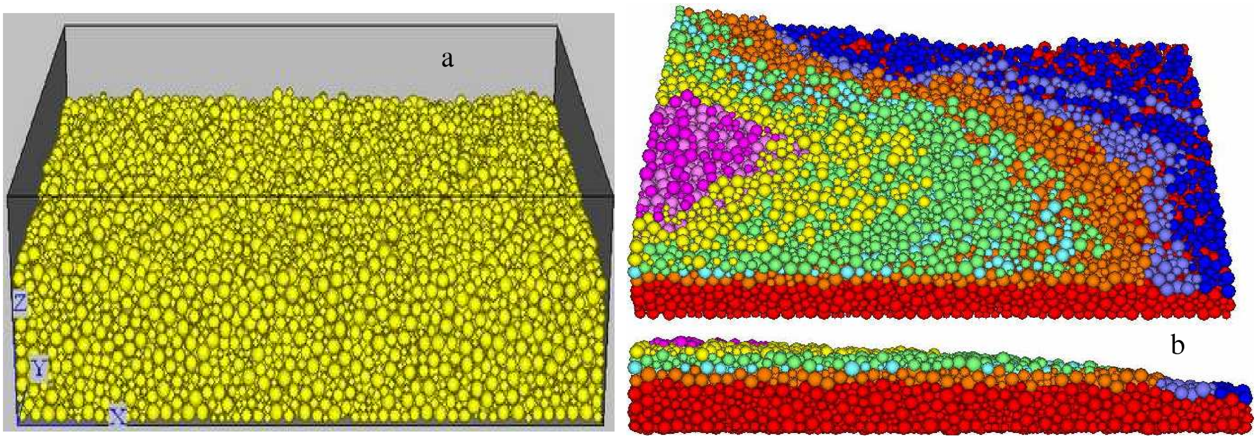

Figure 6: Balls reaching a steady state condition (a) and balls are set in 9 layers (b).

Table 2: The micro-parameters used in PFC model.

No	Material	Particle Density (kg/m^3)	Young's modulus EC (N/m^2)	The ratio of particles normal to shear stiffness kn/ks	Particle friction Coefficient μ(Φ)
1	Tuff sandy clay	2760	7.18E+07	10	0.10
2	Tufaceous clay	2690	4.00E+07	10	0.24
3	Tufaceous mudstone-claystone breccia (2nd period)	2720	9.14E+08	11	0.54
4	Tufaceous mudstone-claystone andesitic breccia	2580	5.00E+07	10	0.60
5	Tuff	2720	8.12E+07	12	0.20
6	Tufaceous mudstone-claystone breccia (1st period)	2640	9.18E+07	12	0.41
7	Tufaceous claystone breccia	2620	9.0E+07	11	0.30
8	Sandy clay	2630	9.2E+07	13	0.61
9	Mudstone-Sandstone	2750	9.18E+07	13	0.54

Table 3: The average unbalanced and maximum unbalanced force during simulation (force unit: kN).

Cycle	0	1000	2000	3000	4000	5000	6000	7000	8000	9000	10000	15000	16998
av-unbal force	90.18	50.84	38.78	23.83	12.19	5.903	5.129	2.89	3.027	3.155	1.448	0.061	0.017
max-unbal force	4212	3733	3353	2093	2538	442.9	877.6	1158	606.3	564.7	269.2	9.256	0.729

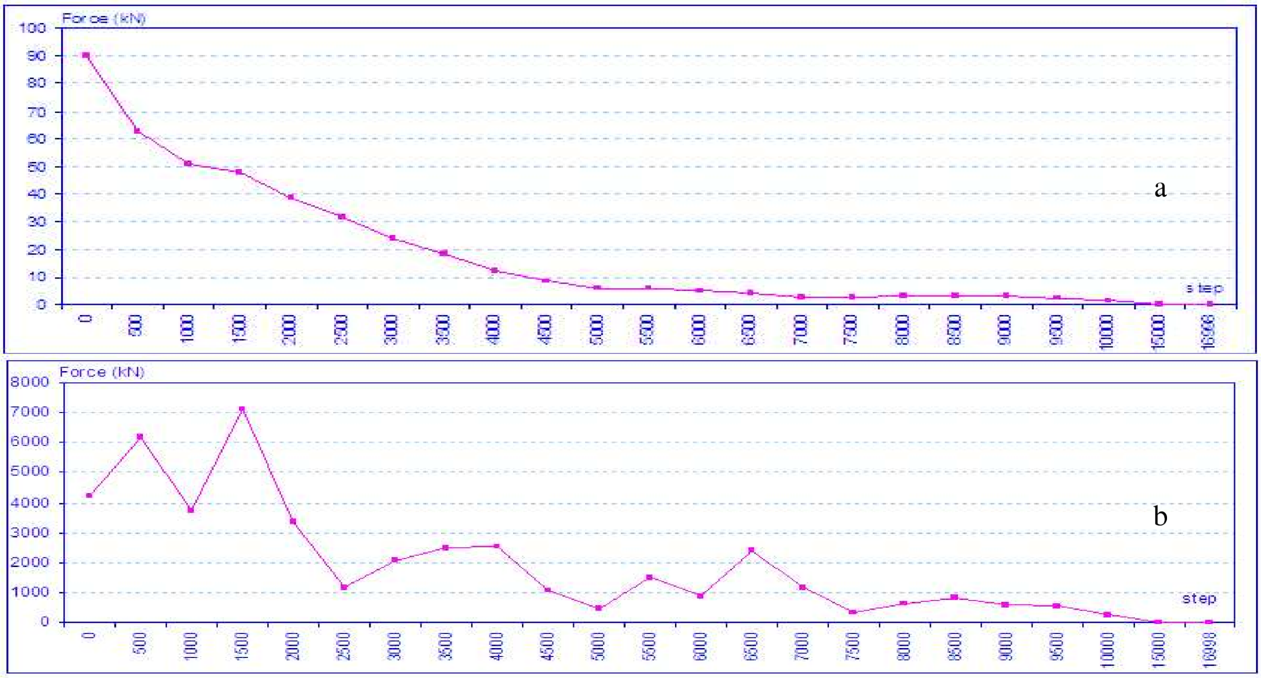

Figure 9: The fluctuation of average unbalanced force (a) and maximum unbalanced force (b) during simulation.

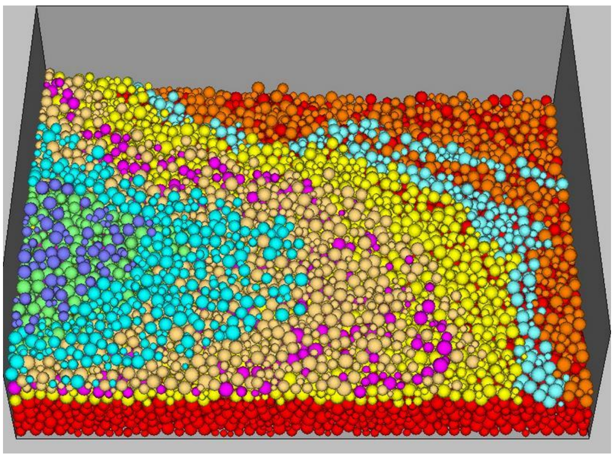

Figure 7: The simulation after 5,000 steps.

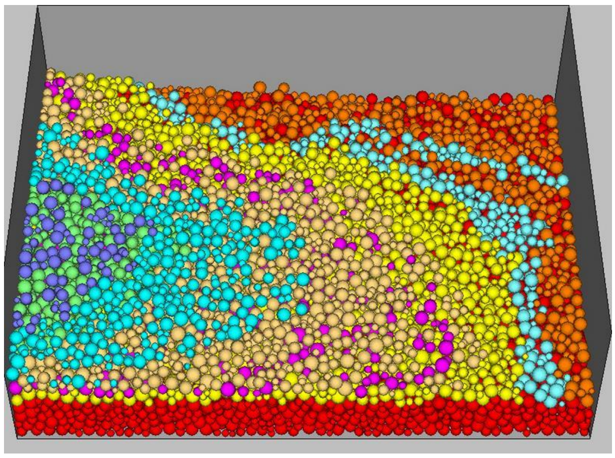

Figure 8: The simulation after reaching equilibrium 16,998 steps.

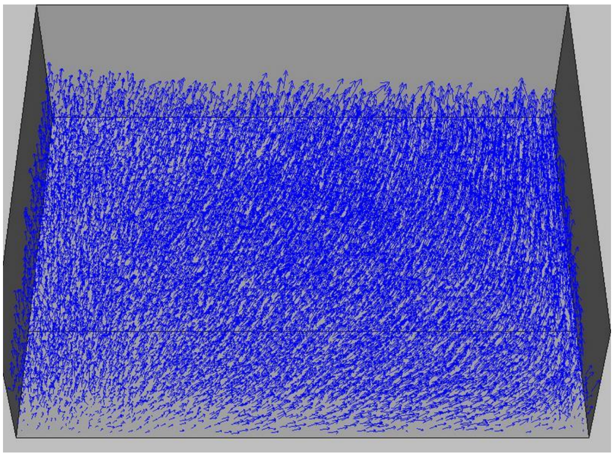

Figure 10: Vector of displacement after 5,000 steps.

Using the program to record the coordinate for each 16.295 balls in every step, the histories of movement as well as the vector of displacements are recognized. The zone of movement is illustrated in Figure 11. Figure 11 illustrates that SG-1 is located in 0-1m creeping zone, SG-2 and SG-3 are located in 1-2 m creeping zone, the SG-4 is located in boundary of 1-2 m creeping zone and 2-3 m creeping zone, while SG-5 is located in 2-3 m creeping zone. The 3-4 m creeping zone runs along the channel. This result also revealed that the 1-2 m creeping zone (violet color) and the 2-3 m creeping zone (yellow color) occupy almost the whole of the scope area. These are the zones which caused the deformation of the channel and the bridge.

The PFC^{3D} result is in agreement with the monitoring result not only on the creeping zones (Figure 11) but also on the directions of movement. The vectors of displacement are close to directions of movement by monitoring result, (Figure 12).

5 Conclusions

In spite of limitation of number of balls as well as ball sizes, the very big balls cannot represent exactly the thin layers of this slope. The PFC^{3D} simulation results are still in agreement with the monitoring result not only on the creeping zones but also on the direction of movements.

Although the balls within the mudstone layer

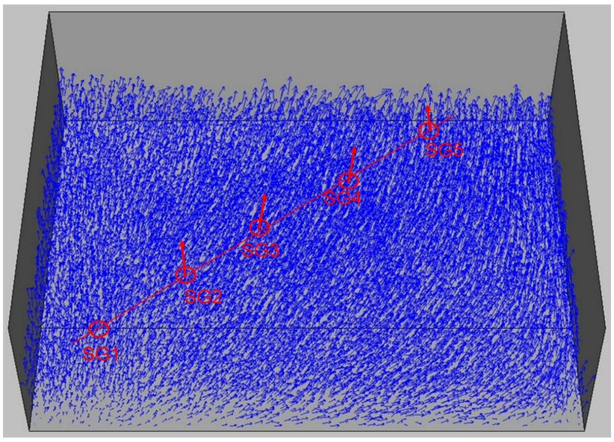

Figure 12: The vectors of displacement comparing with direction of movements by monitoring result.

are creeping, the creeping zone map and displacement vectors map of PFC^{3D} result are still in agreement with the monitoring result. Writing program code to record the coordinate of each ball in every step for recognizing the histories of movement as well as the vector of displacements to make the creeping zone map is a new idea in this research. The creeping zone map of PFC^{3D} could be applied for slope movement in the field.

Under the circumstances of time limitation and research condition, the chosen PFC model is the most appropriate model which could be applied for slope movement of this area as well as in other areas with the same condition. The PFC^{3D} model is not only being used for predicting displacement of movement but also for predicting direction of movement.

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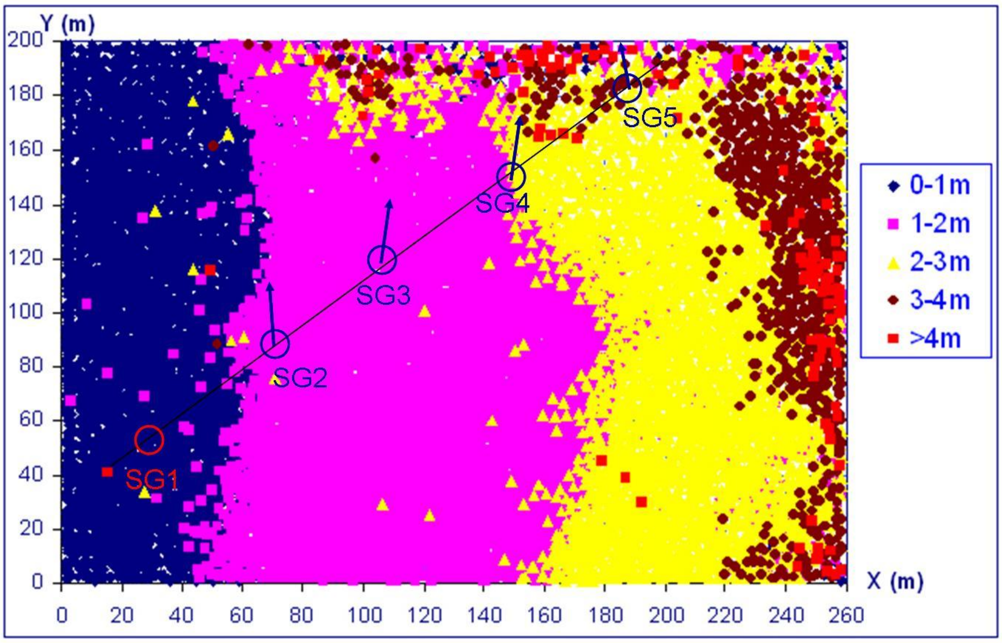

Figure 11: The creeping zone map in PFC^{3D} comparing with monitoring result.

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