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STABILITY STUDY OF THE MINE OVERBURDEN DUMPS SLOPE: A MICROMECHANICAL APPROACH

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Abstract: Discontinuum based particle–particle interaction mechanics is applied to the modeling of waste composed of fragmented rock and loose soil produced at the opencast coal mines. The distinct element method considered the discrete nature of geomaterials and represented them with bonded and unbonded matrix assembly. The overburden dump material is studied with laboratory test of synthetic material, similar to physical testing and calibration done through that. The next part focused on the static stability characteristics of the overburden dumps with heavily joint set and performance study was done on the ability to model it. The location of sliding is visualized via numerical code. The last part deals with the performance characteristics of the overburden dumps under seismic loads. The history of the responses at monitoring points is studied for interpretation of the dynamic behavior of the overburden dump mass. The responses are used to determine the natural frequency of the overburden dumps, damping fraction and the phase difference at two sides of the dumps mass. The results obtained match well with fundamental concept of the vibration theory.

1. INTRODUCTION

Thick layers of shallow deposit coal are exploited by removing the top overburden (OB), called open pit mining. The extent of exploitation and increasing depth generates multiplied amount of OB, and necessitates proper handling of the material. The fragmented rock and loose soil makes the degree of interaction a difficult proposition in view of structural stability [18]. Soils and rocks are composed of grains and deformation and failure due to loading result in disintegration of their structure. To simulate the structural changes of these particulate materials [8], [24], sophisticated constitutive models, higher-order continua, and different numerical techniques are used in continuum mechanics. The larger the disturbance of the structure that occurs, the more complicated theory is necessary in order to simulate it. This is due to the fact that phenomena of a discontinuous nature are to be described by means of continuum mechanics.

The Distinct Element Method (DEM) [3], [31] provides an alternative, discontinuum mechanics approach to the modeling of the mechanical behavior of geological materials [32]. With the developments of DEM [25], soils and rocks are represented as an assembly of unbonded or bonded particles [16], and their macroscopic behavior arises from the properties and the interaction of microscopic constituents. The discrete character and complex behavior of particulate materials could be simulated at macroscale (dilation, strain localization, slip, strain softening, etc.) by applying simple laws and parameters on the microscale. Proper visualization of particle interaction allows linking the responses at macroscopic and microscopic levels.

This information can be used in two ways. First, it may contribute to constitutive modeling of complex geological materials [9], [22] in an indirect way, in the framework of continuum mechanics. If the micromechanical model matches the laboratory test results of the physical material, then the experimental results can be interpreted from a structural point of view. This means that different deformation and collapse mechanisms observed at macrolevel can be explained by related interaction at microlevel and vice versa. This approach contributes to the formulation of appropriate, physically based constitutive models of geomaterials for engineering applications [19]. The highly versatile approaches such as Disturbed State Concept (DSC), which accounts for microstructural effects in an indirect way [4], may gain some additional, useful information from an appropriate micromechanical model. Provided the micromechanical model matches the behavior of the intended physical material, constituents of the disturbance function (ratio of disturbed and undisturbed interparticle bonds, area of voids to area of solid particles, etc.) and their development can be quantified and an incremental form of disturbance function determined.

The second way is a direct discontinuum mechanics or micromechanical approach [5], which consists of the following steps. A specimen of synthetic material is generated in accordance to the basic characteristics of the physical material. Simulated laboratory tests of the synthetic material are calibrated, with that of physical material. If this is successful, then the next step is merely the solution of the boundary problem under consideration, using the synthetic material. In this direct approach, there is no need for complete mathematical description of the phenomenological behavior of physical material. Instead, an inverse problem is solved aiming at determining the micromechanical properties and other parameters (particle size, porosity, initial stress) of a synthetic material, which produces the macroscale response of a physical material.

The above research has so far been restricted to simulating laboratory tests of bonded and unbonded granular material [15] without an attempt to use the direct micromechanical approach for real life boundary problems (structures like dam, embankment, mine). The latter is the domain of recent development in modeling real life problems [27], [33] with proper visualization of the results at particle level. This is due to rather demanding coding of micromechanical versions of DEM [14], [29], [30], concerning both the runtime optimization and the visualization at particle level. In view of that, it was decided to make use of available codes in two dimensions, and the capabilities of the code to model noncohesive and cohesive particulate materials were investigated.

In this article, a part of this research concerning micromechanical modeling of a fragmented sandstone [5], a dump material produced by open-pit coal mines is presented. To model this material of complex structure, two synthetic materials matching the mechanical response of the physical materials had to be created: sandstone, as a bonded cohesive material with strong structure and a dump material, as a jointed material with weak structure. The objective of the study was twofold. First, in order to support the continuum-based constitutive modeling, the structural effects at micro- and macrolevel were studied and hereby presented. Second, in order to perform a direct micromechanical approach, dump geometry was prepared using synthetic material and solving the static as well as dynamic loading performance of the problem. The constitutive interaction mechanism has been governed by the fine tuned synthetic material. This is studied and simulated in the first part of the work. And it is integrated with the validation study of the material. To model this part discontinuity surface, i.e. joints were incorporated to match the in situ conditions. Mechanical response of inter particle contact and bonded cohesive material behaviors are studied initially with self weight of the large external dumps and the strain localization, displacement observed at critical points and the same are observed under earthquake loads. The dynamic loading was carried out with a few more monitoring points to acquire simulated stress-strain profile with progressive earthquake excitation time history to get better insight into the natural frequency of mine dump and associated damping scheme.

2. DESCRIPTION OF THE DUMP MATERIAL

At Western Coalfields Limited, Nagpur, a productive open pit mine of up to 20 m thick coal seam is covered by approximately 120 m thick overburden consisting of soil, clay, gray shale, coarse to medium grained sandstone, sandy shale, shaly sandstone, which are considered in this study. The overburden is excavated and the fragmented dump material is deposited in huge uncompacted dump occupying an area of more than a few square kilometers. To ensure the dump slope stability, to estimate the settlement, the properties of the dump material should be determined. These depend on both the quality of the sandstone fragments (size, internal porosity, degree of weathering, uniaxial strength) and the method of dumping and are considerably influenced by further loading conditions (vehicle movement, blasting, earthquake and rainfall, etc.) and time. Due to these factors, the originally fragmented rock and loose soil of the mine OB is changed into complex assembly presenting considerable difficulties.

External dump of the NavinKunada (NKD) open pit coal mine was planned for designing with optimum height and slope angle to save land and the compaction and strength properties of the upper part of the dump material were determined. The triaxial and shear box laboratory tests on NKD dump material were used for verification of the numerical simulation.

The direct shear test of the fragmented sandstone at dump site is represented by the following parameters: deformation modulus E = 25–40 MPa, Poisson's ratio ν = 0.21, angle of friction φ = 23°–28°, cohesion c = 0–200 KPa, porosity n = 25%, density ρ = 2300 kg/m^3, uniaxial strength of intact rock σ_c = 0–2 MPa. Properties of the loose OB at dump sites vary in the following range: E = 2–15 MPa, Poisson's ratio ν = 0.18–0.30, angle of friction φ = 12°–35°, cohesion c = 10–100 KPa, undrained shear strength c_u = 50–120 KPa, φ_u = 0°, n = 35%, ρ = 1950 Kg/m^3, average grain size d_{50} = 2 mm. The parameters of NKD dump material used for comparison are as follows: E = 4–12 MPa, Poisson's ratio ν = 0.30, angle of friction φ = 12°–28.5°, cohesion c = 65–120 KPa, ρ = 1870 Kg/m^3. It is observed from the triaxial test results that initial deformation modulus decreases with increasing cell pressure. This indicates internal collapse of the sandstone fragments due to consolidation. To get an insight into the mechanical behavior of this complex dump material at microlevel, the distinct element method [25] was adopted.

3. DESCRIPTION OF THE CODE AND THE NUMERICAL TESTING PROCEDURES

3.1. BASIC FEATURES

PFC2D is a distinct element code that is oriented on micromechanical modeling of unbonded and bonded particulate materials [25]. It is a simplified implementation of the Distinct Element Method (DEM) restricted to an assembly of rigid circular particles of variable radius. This two dimensional assembly can be interpreted as a collection of variable-radius cylinders, where the out-of-plane forces are not considered. In addition to particles, walls are included for confinement of the assembly and application of boundary conditions. According to the soft-contact approach applied, the rigid particles are allowed to overlap at contact points. The stiffness of the contact and thus the overlap are determined by the constitutive law, which relates contact forces to relative displacements of particles at contact points. The following contact models can be used: linear and nonlinear contact stiffness model, slip model, contact bond model (tensile and shear contact bond strength), and parallel bond model providing the effect of cement matrix. The interaction of particles is modeled as a dynamic process using a time-stepping algorithm. The method is based on the idea that the time step chosen may be so small that, during a single step, disturbances cannot propagate further from any particle than its immediate neighbors. Due to this assumption the governing system of equations is fully decoupled and the solution scheme is explicit in space and time. A rather large number of steps (from 3000 up to 100,000) are necessary in order to achieve a state of quasistatic or dynamic equilibrium. The calculation cycle performed in each time step consists of two parts: the application of a force/displacement law at all contacts and Newton's second law to all particles. The equation of motion is integrated using a central finite difference scheme.

PFC2D provides a facility to measure the average stress and strain-rate tensor, the porosity and number of contacts per particle within the particle assembly. Furthermore, there is a built-in programming language for modifying the analysis and extensive graphics facilities to plot variables and behavior of the assembly at particle level.

3.2. PROCEDURES OF THE NUMERICAL TESTING

PFC2D version 3.1 is a command mode program also running in the Windows environment. The model must be programmed in the built-in language FISH using command prompts in the PFC2D environment. This process can be simplified by calling pre-written data files from PFC2D. It is also useful for dividing simulation into several logical stages when modeling time-consuming problems. Hardware requirements depend on the number of particles and complexity of the model. In order to match the behavior of the dump material, it was necessary to perform numerical tests that simulate laboratory tests on physical samples. The problem was divided into two phases. First, a numerical model of synthetic material was created and tuned to match the deformational and strength characteristics of the OB material, which forms the fragments of the dump material. Second, applying discontinuities in two directions weakened the obtained numerical model of the synthetic material. Essentially, the discontinuities were lines where the contact bonds between particles along the lines and the shear and normal stiffness of the contacts were reduced. The fragmented sandstone and loose soil represent the dump material, and it was also tuned to match the deformational and shear strength characteristics of the real dump material.

The numerical biaxial test described in the PFC2D user's guide was taken as a base for inverse modeling of the OB dump material. Generally, the numerical simulation (both for the synthetic material and the OB dump material) consisted of the following stages: generation of the assembly of particles, introduction of initial confining stress, and loading the sample (shearing). This logical division of the problem was also respected during entering data files. The actual state of the model was saved after each stage. This made it possible to vary the input parameters and model conditions in later stages without the necessity to perform the whole computation.

PFC2D supports gluing the particles at the contact points to simulate cohesive behavior by two bonding models: parallel bonds and contact bonds. A contact bond model for modeling the bonds between the particles was used in this work. The contact bond has the effect of adhesion acting at the point of contact between particles, and it provides a tensile normal and shear contact strength to each contact point. If the magnitude of the tensile normal contact force exceeds the normal contact bond strength the bond breaks and both the normal and shear contact forces are set to zero. If the magnitude of the shear contact force exceeds the shear contact bond strength, the bond also breaks, but the contact forces are not altered [25]. The presence of a contact bond inactivates the slip model that is defined by a factor of friction. The factor of friction at microlevel was held to be zero for all the numerical tests in order to simulate the lower friction angle of the clayey materials under consideration.

3.3. GRAPHICAL PRESENTATION

The graphical interface of PFC2D provides tools for graphical interpretation of measured quantities (history graphs) and for monitoring various features of an assembly at any moment during the simulation (before and after failure). Relations between deviator stress vs. axial strain and volumetric strain vs. axial strain were plotted to study the deformation, strength, and volumetric response of the sample.

3.4. INPUT PARAMETERS

All input parameters with corresponding abbreviations used on the model are summarized in the following table:

Normal interparticle contact stiffness	*n_stiff or kn*	[N/m]
Shear interparticle contact stiffness	*s_stiff or ks*	[N/m]
Particle–wall contact stiffness	*w_stiff*	[N/m]
Density	*dens*	[kg/m^3]
Velocity of loading	*m_vel*	[m/s]
Shear contact bond strength	*s_bond*	[N]
Normal contact bond strength	*n_bond*	[N]

4. MICROMECHANICAL MODELING

4.1. GENERATION OF THE ASSEMBLY OF PARTICLES

Rigid circular particles of required radii were generated within the specified area confined by four walls. The overlapping of particles was not allowed. The desired porosity of the assembly was obtained by radius expansion. In this approach, a number of particles with relatively small radii are placed within the area and then the radii are expanded to reach the desired porosity. During the generation of the assembly of the particles only the normal and shear contact stiffness, friction, and density are introduced without a specification of the tensile and shear contact bond strength. The geometry and stiffness of the discontinuities (when modeling the jointed material) were also specified during this stage.

Uniform micromechanical properties and contacts are considered in this study. The number of particles generated was 1976. The initial assembly of synthetic material is shown in figure 1. The density of the particle is set to 2300 kg/m^3. Interparticle normal and shear contact stiffness, particle–wall contact stiffness and factor of friction are also set during generation stage.

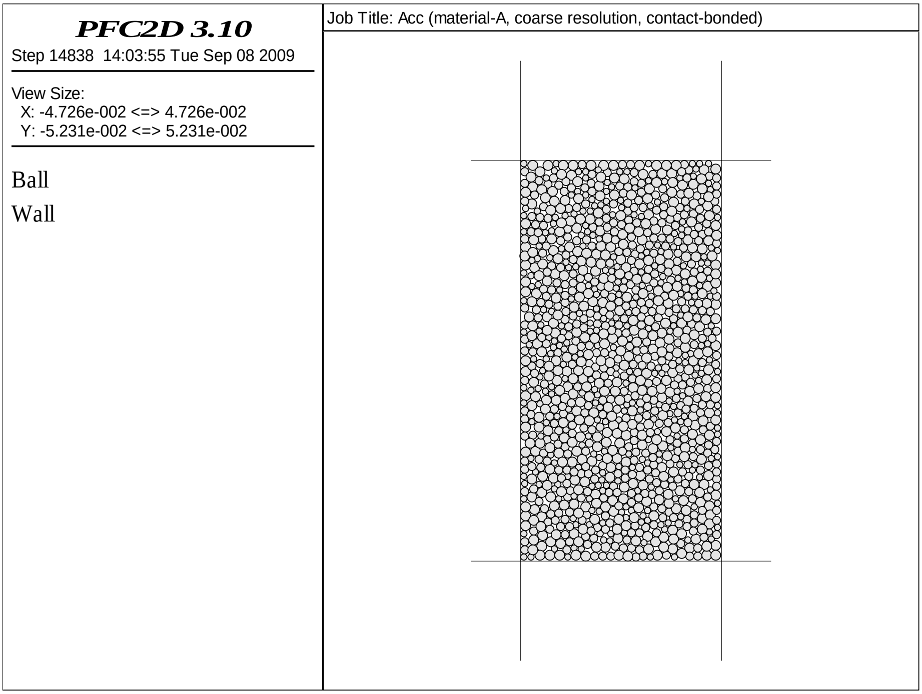

Fig. 1. The synthetic material for micromechanical model of OB dump soil sample

4.2. INTRODUCTION OF INITIAL STRESS STATE

To achieve a desired value of initial stress the sample was loaded by movements of the top and bottom walls. The initial loading corresponds to the consolidation phase of a physical test and the micromechanical properties were the same as in the generation phase. The stress was kept constant using the implemented servomechanism controlling the lateral walls velocities. History variables (confining stress, deviator stress, axial strain, and volumetric strain) that are necessary for interpreting the test results were defined during this stage. History variable values were logged for every 50th step.

4.3. TESTING PROCEDURE

Prior to loading the micromechanical characteristics of contact bonds (normal and shear contact bond strengths) were entered. Different values of contact bond strengths within the sandstone fragments and between them (at discontinuities) were specified to model the fragmented physical material.

Servo control for the top and bottom walls was released and then they were accelerated to the final velocity imposed loading (shearing), while the confining stress was kept constant. The loading was stopped after reaching an axial strain corresponding approximately to critical state – no more significant volume change during additional shearing. Initial deformation characteristics were determined from a small initial loading and unloading cycle performed on the sample by changing the movement of the walls to the opposite direction.

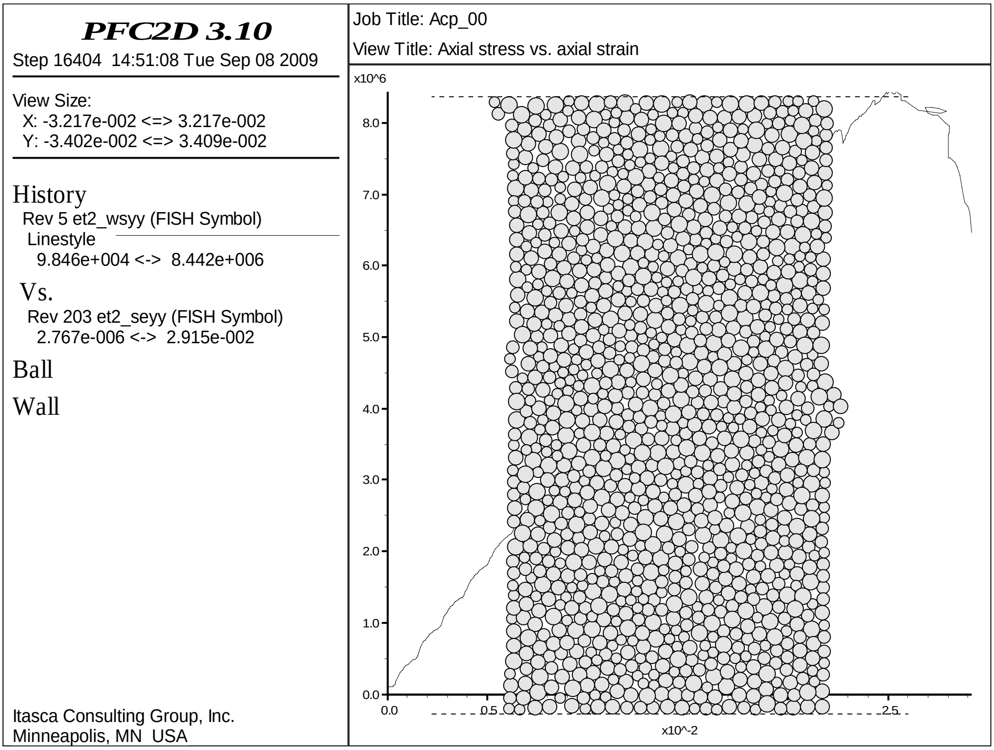

Fig. 2. Stress-strain response of OB dump soil with zero confining pressure

The stress-strain responses with and without confining stress are shown in figures 2 and 3, respectively. The strength is plotted against the increasing confining pressure in figure 5, with the half value of the linear part in the stress-strain characteristics curve (example figures 1 and 2). A linear increase of the deformation modulus is observed with increasing confining pressure (shown in figure 4).

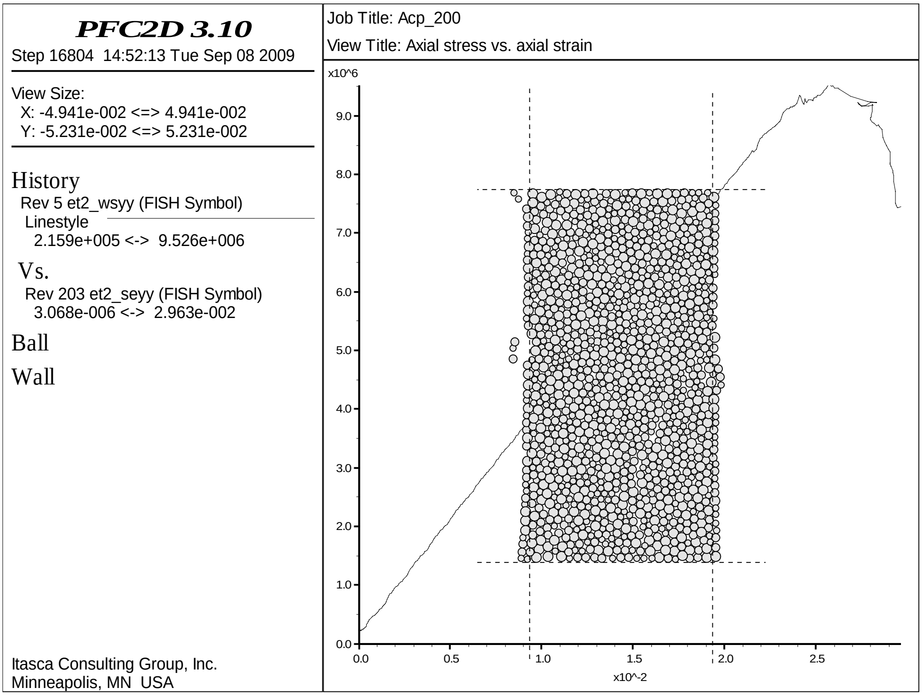

Fig. 3. Stress-strain response of OB dump soil with confining pressure (200 KPa)

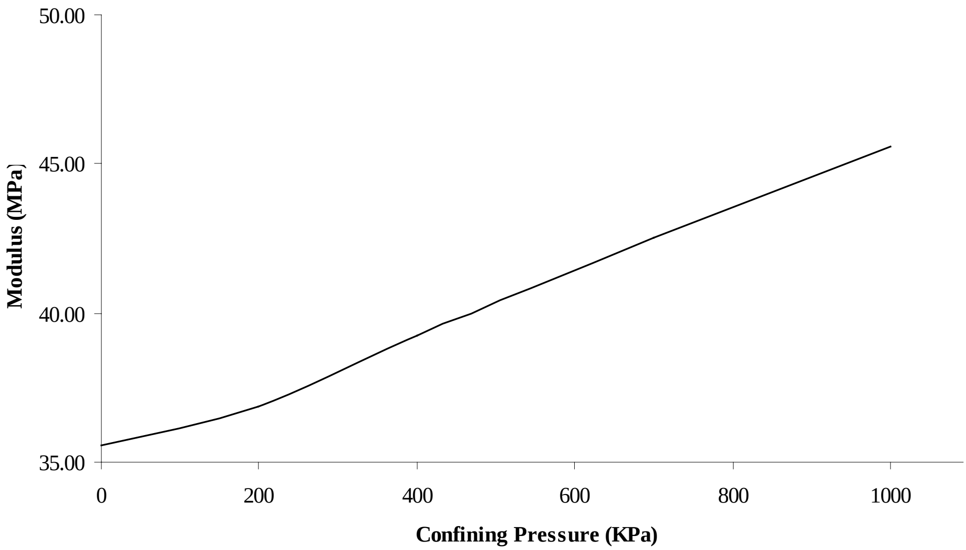

Fig. 4. The deformation modulus from simulation test on synthetic material

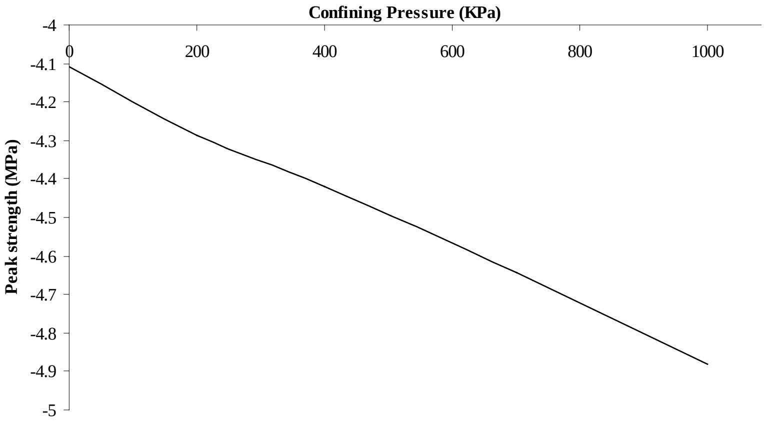

Fig. 5. The peak strength from simulation test on synthetic material

5. PFC2D MODEL OF A DUMP SLOPE

The simulation of a dump slope was carried out with a four-step procedure.

5.1. GENERATION OF THE PARTICLE ASSEMBLY WITH INTACT ROCK PROPERTIES

A rectangular assembly 95 m wide and 50 m high was created using 8,787 particles whose properties were calibrated in the PFC calibration stage (discussed in the above section). Figure 6 shows the dump slope with ball assembly. The smallest and largest particle radii are 25 cm and 26 cm, respectively. There is no joint and gravity in the assembly at this stage. Thus, every part of the model has the same intact rock properties as described above. The 8,787 particles that comprise the assembly consist of two groups of particles, one at base and another as dump profile with the above-mentioned radii.

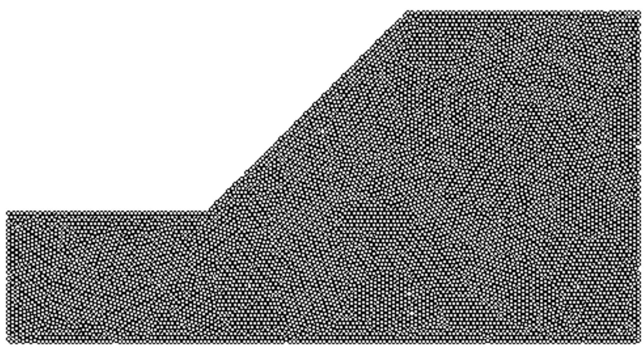

Fig. 6. Overburden dumps are generated with a ball of the synthetic material

5.2. INITIALIZATION OF IN SITU STRESS

A gravity induced in situ stress was applied to the model. Based on an average density dump material of 2300 kg/m^3, a maximum vertical stress of approximately 1.12 MPa was developed at the bottom boundary of the 50 m high assembly, with the proper radius expansion and stable condition being achieved after several thousand cycles of operation.

5.3. GENERATION OF JOINTS

Joints are the most common feature in the mining geology [13]. They are defined as cracks or fractures in rock along which there has been little or no displacement. They usually occur in sets which are more or less parallel and regularly spaced; also there are usually several sets in different directions so that the rock mass is broken up into a blocky structure. Thus, the material is not a mathematical continuum, but is divided into a number of parts by joint surfaces along which sliding may take place.

In PFC2D, joint planes can be defined individually or as a set of planes, and such sets can be combined to create a multiple-intersecting, jointed or blocky system. A PFC2D model can have as many joint sets as desired. Each joint set may have multiple joint planes that are separated from each other by a specified spacing. The definition of joint spacing in PFC2D is the same as in rock engineering practice, i.e. the perpendicular distance between adjacent discontinuities [10], [25].

Parameters used in this study also include origin, dip, maximum joint segment length and number of joints in each joint set. The dip of a joint is defined as an angle of the joint plane, in degrees, measured clockwise from the positive X-axis. The origin is a point on the joint plane. With the origin, the first joint plane can be located and the rest of the joint planes in the same joint set can be placed according to the specified joint spacing of the same joint set.

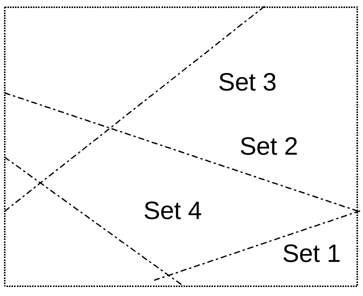

Fig. 7. The four joint sets orientation created at the OB dumps model in PFC2D

A total of four joint sets were created in the OB dump model. Their orientations are illustrated in figure 7. The characteristics of each joint set are identical. The joint spacing was 10 m. Dip angles ranged from –45° to 40°. The origins used in this study were specified at PFC2D and the joint numbers were large enough to ensure that every portion of the OB dumps mass had uniformly distributed joints.

6. SLOPE STABILITY WITH THE PRESENCE OF JOINTS

Evaluation of discontinuities in a geological rock mass has long been a major part of engineering rock mass classification where the attributes of discontinuities play indispensable roles. For example, the currently widely accepted RMR [1] and Q-System [12] use spacing, surface roughness, separation (aperture), infilling, weathering, orientation, joint set number, etc., along with other rock mass properties to evaluate a rock mass. Hudson and Harrison [12] described the discontinuities in rock masses by using geometrical properties and mechanical properties based on the ISRM standard. In PFC2D modeling, these properties can be classified as joint quantity and quality. Properties such as spacing, joint set number, joint persistence can be described as the quantity of rock mass discontinuities, while surface roughness, infilling, weathering and so on can be treated as discontinuity qualities. Discontinuity quality can be comprehensively reflected by the mechanical behavior of a joint.

The discontinuity quality can be simulated in PFC2D by assigning properties to each joint set individually. For instance, assigning a different friction coefficient, particle stiffness and a weak bond to particles along a joint plane can be used to simulate a wide range of mechanical properties of a joint.

6.1. DUMP SLOPE FAILURE

The development of slope failure shown in figure 8 facilitates the understanding of where the failure starts, how it starts and develops. It also shows how each of the destabilized blocks of OB moves and where breakage of OB mass is involved during the development of the failure. With this knowledge, a rock engineer can undertake fur-

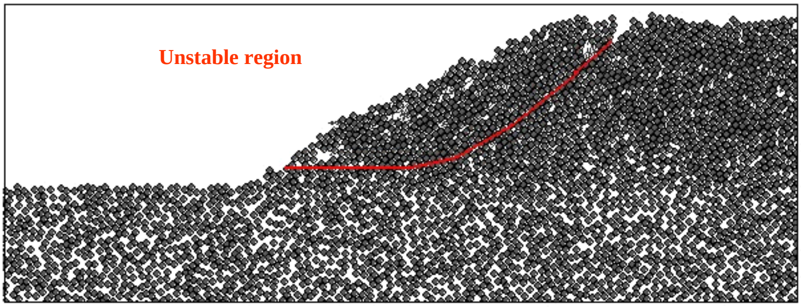

Fig. 8. Slope failure development of an OB dumps soil mass with four sets of joints

ther study on the stability control strategy so that it is more relevant and effective, and design the rock slope on a more scientific basis.

7. SLOPE STABILITY WITH THE SEISMIC LOADING

The discrete element method (DEM) is a powerful tool for the stability analysis of external overburden dumps during wave propagation at seismic events [2], [11], [17], [20]. The explicit solution in the time domain used by DEM is appropriate for following the time propagation of a stress wave. The boundaries defined in this method should permit energy radiation and do not reflect outward propagating waves into the model. Viscous damping elements developed by Lysmer and Kuhlemeyer [21] are not used, instead local damping was used in this investigation similar to hysteretic damping. The local damping is frequency-independent, and the regions of the OB mass with different natural periods are damped equally, with this damping constant.

7.1. SEISMIC VELOCITY HISTORY

The determination of input dynamic load is the basic information and a difficult proposition in the study of dynamic response of OB dumps slope under earthquake. The velocity history obtained by field measurements close to the ground level at Imperial Valley (El-Centro, in 1940, A_{max} = 0.313 g, earthquake magnitude = 6.95) is adopted as the input load directly, as shown in figure 9. Details of the El-Centro seismic wave are given in table 1.

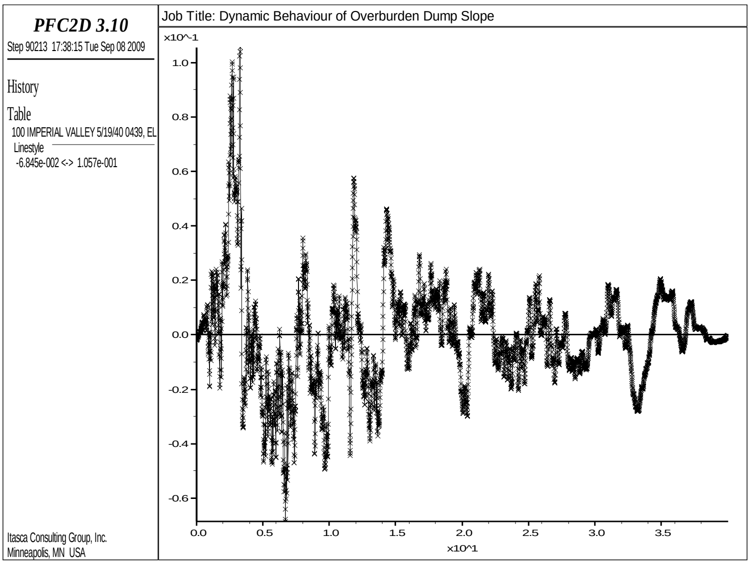

Fig. 9. Input earthquake excitation applied to the numerical model in PFC2D

Table 1

The basic data of seismic waves recorded in El-Centro of the Imperial Valley, USA

Platform for observing earthquake	Earthquake magnitude	Date	Component orientation	Peak velocity (cm/s)	Number of record points	Time intervals (s)
117 El Centro Array #9	7.0	19/05/1940	IMPVALL/I-ELC-UP	10.7	4000	0.01
117 El Centro Array #9	7.0	19/05/1940	IMPVALL/I-ELC180	29.8	4000	0.01
117 El Centro Array #9	7.0	19/05/1940	IMPVALL/I-ELC270	30.2	4000	0.01

7.2. TIME HISTORY ANALYSIS

The time history response study is one of the most important parts of the dynamic behavior study of any structure. In this investigation, twelve monitoring points are specified at the initial stage of the modeling. The dynamical response is retrieved back with specified history file. This part of the study involves a large set of data. The problem is subdivided into small substeps to observe and analyse the response spectra. Here, the data are interpreted at four occasions, after 1 sec, 3.5 sec, 9 sec and 14 sec of the application of load. Figures 10 through 16 describe the time history of the dumps mass.

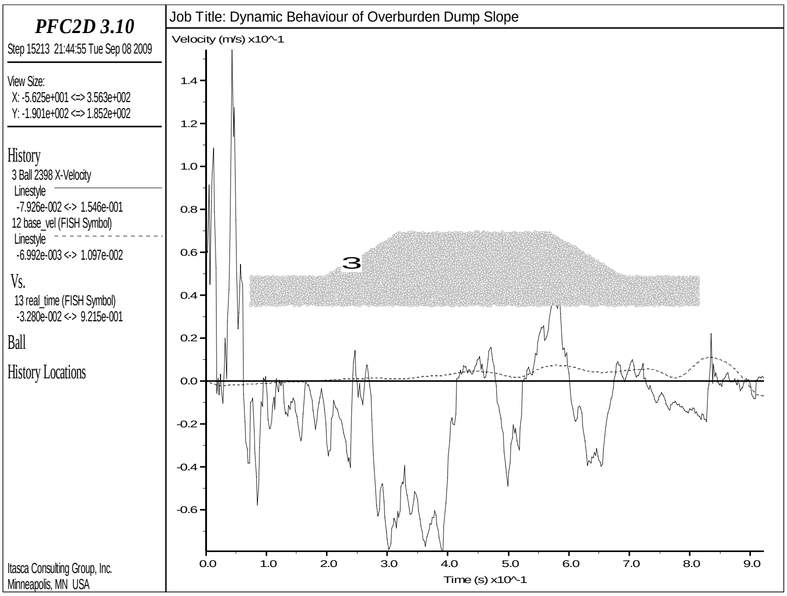

Fig. 10. Earthquake response at the OB dump slope, approx. 5 m above the toe (left-hand side) after 1 sec

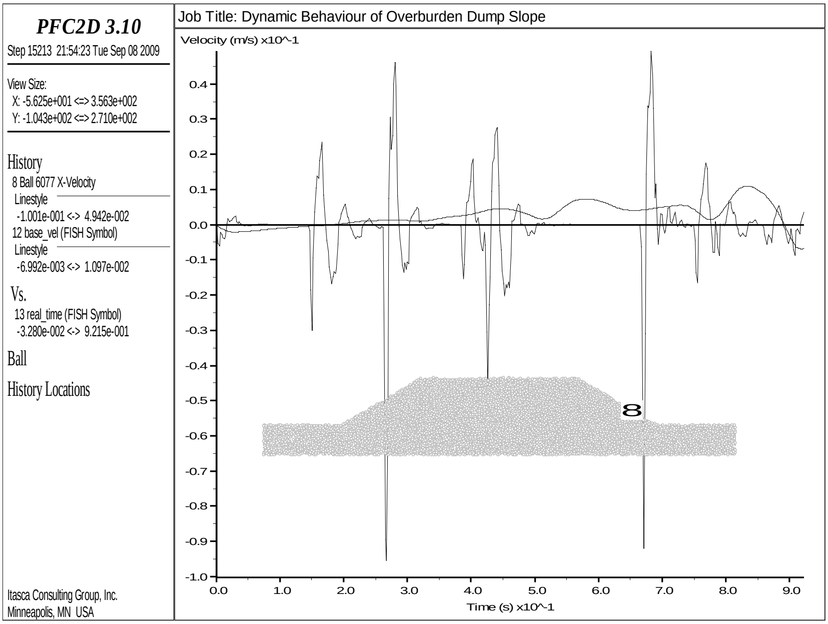

Fig. 11. Earthquake response at the OB dump slope,
approx. 5 m above the toe (right-hand side) after 1 sec

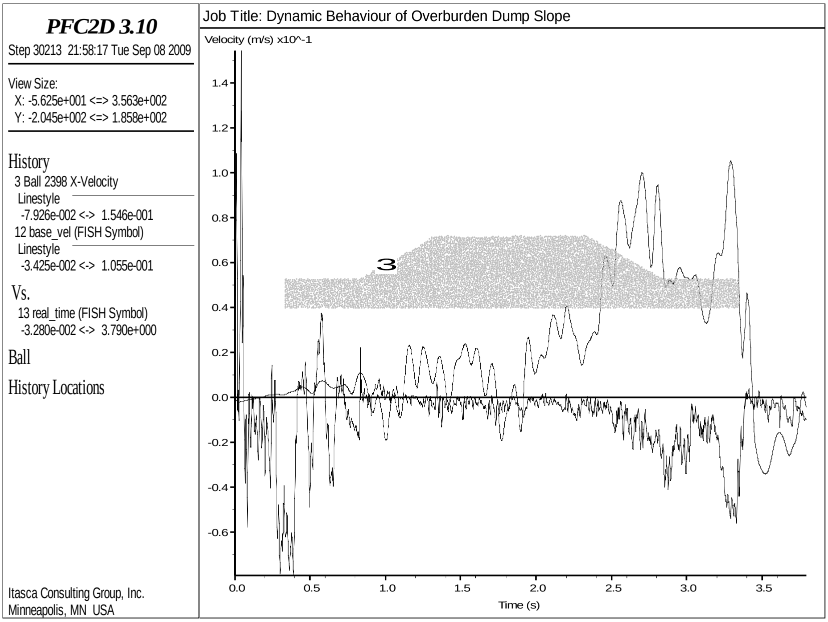

Fig. 12. Earthquake response at the OB dump slope,
approx. 5 m above the toe (left-hand side) after 3.5 sec

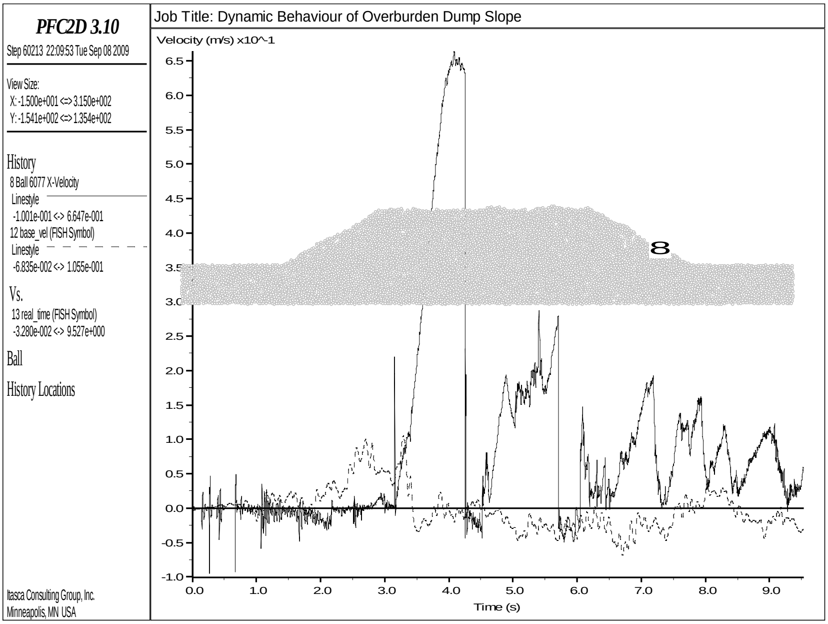

Fig. 13. Earthquake response at the OB dump slope,
approx. 5 m above the toe (right-hand side) after 9 sec

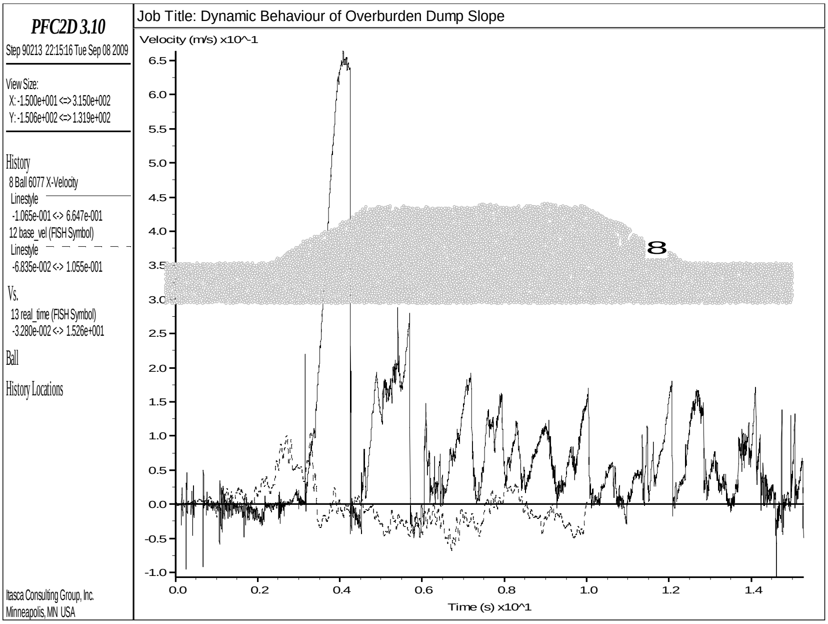

Fig. 14. Earthquake response at the OB dump slope,
approx. 5 m above the toe (right-hand side) after 14 sec

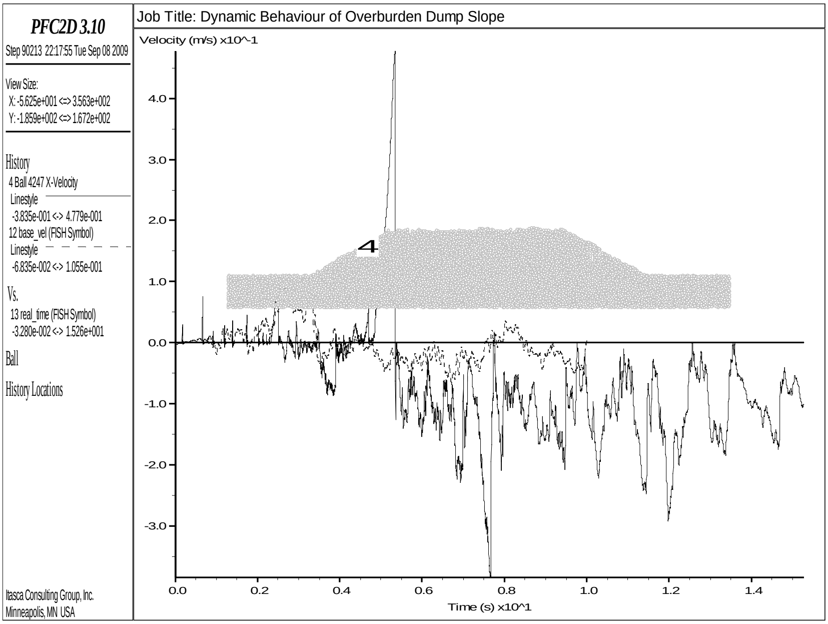

Fig. 15. Earthquake response at the OB dump slope, at the top surface (left-hand side) after 14 sec

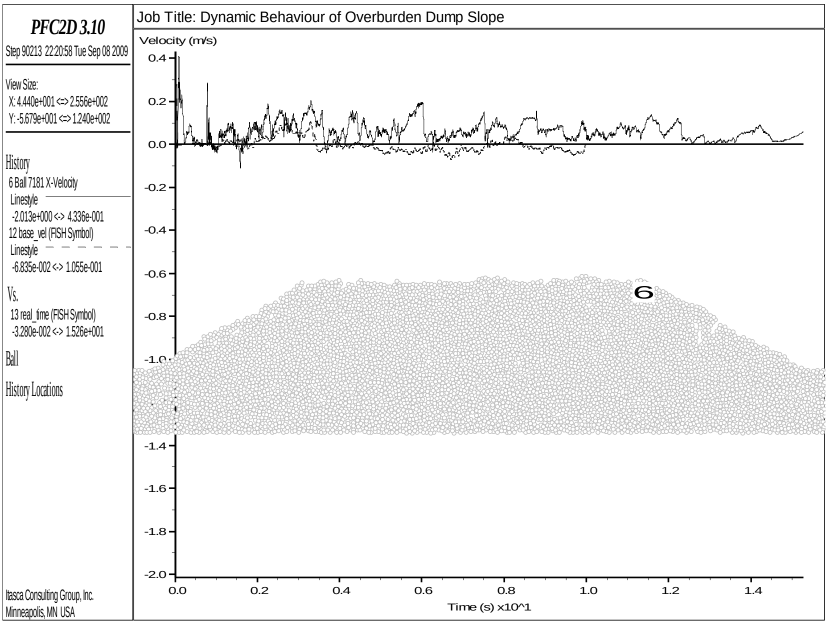

Fig. 16. Earthquake response at the OB dump slope, at the top surface (right-hand side) after 14 sec

7.2. DISPLACEMENT PROFILE

The OB dumps slope is showing progressive failure pattern with the earthquake excitation shown in figures 17, 18, 19 and 20 after 1 sec, 3.5 sec, 9 sec and 14 sec, respectively. A maximum 4.78 m sliding is observed after 14 sec. of the seismic load shown in figure 20.

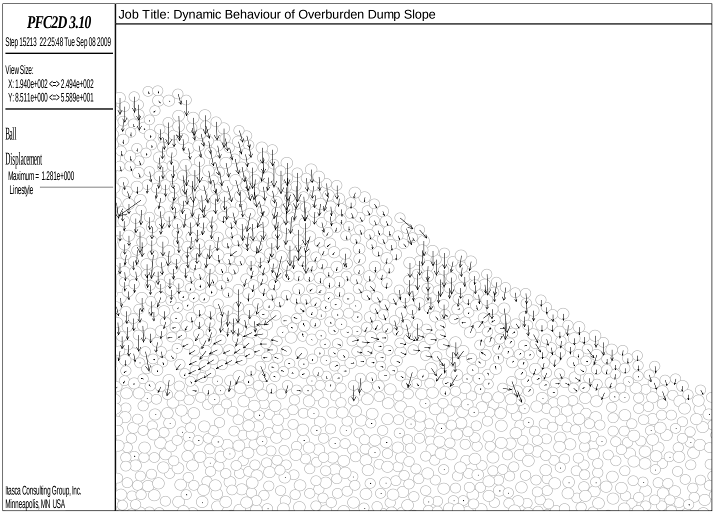

Fig. 17. The displacement profile after 1 sec of the earthquake loading with maximum displacement of 1.28 m along the OB dump surface

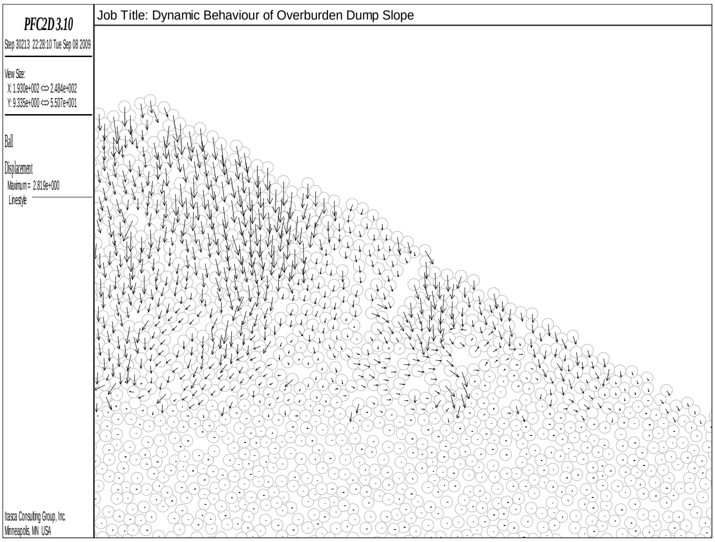

Fig. 18. The displacement profile after 3.5 sec of the earthquake loading with maximum displacement of 2.82 m along the OB dump surface

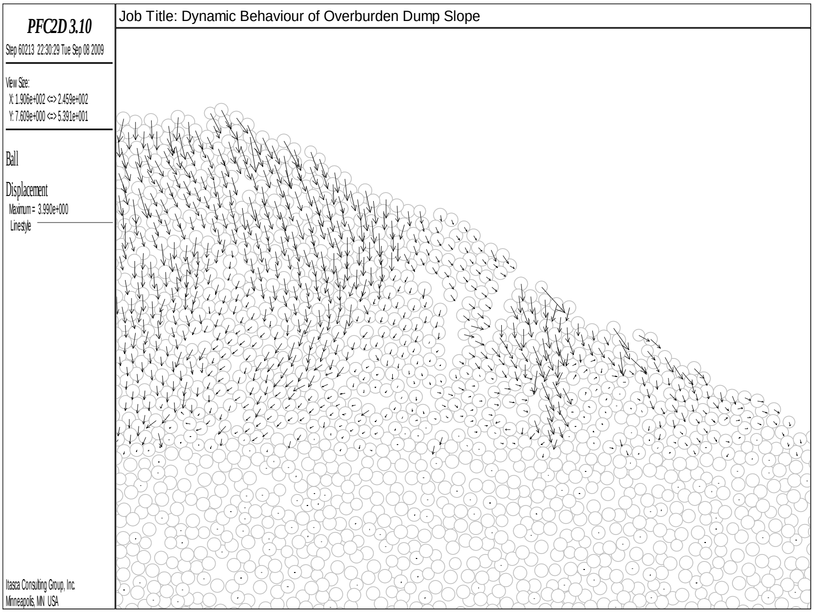

Fig. 19. The displacement profile after 9 sec. of the earthquake loading with maximum displacement of 4 m along the OB dump surface

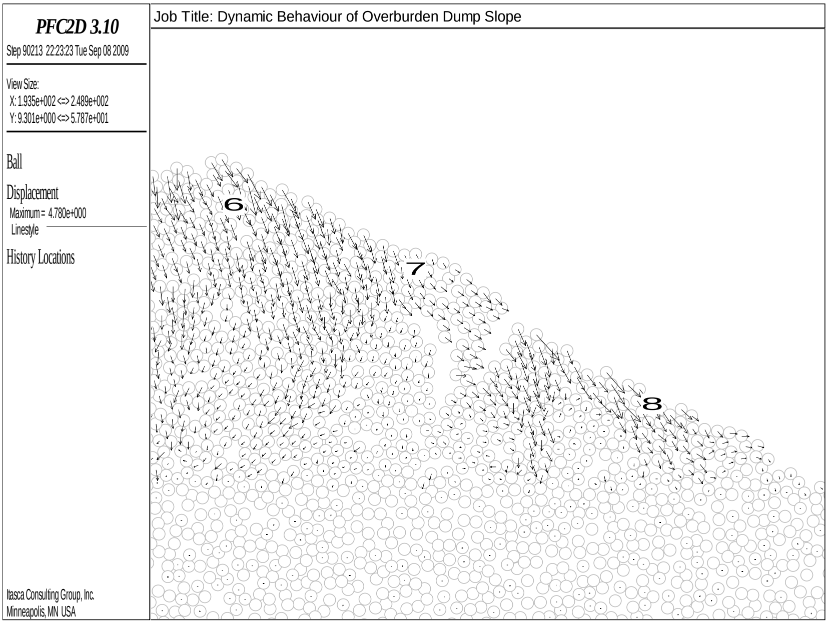

Fig. 20. The displacement profile after 14 sec of the earthquake loading with maximum displacement of 4.78 m along the OB dump surface

8. RESULTS AND DISCUSSION

Natural frequency:

According to the Newmark and Hall [23] equation the natural frequency of a structure can be estimated as the following;

$$f = \sqrt{\frac{L}{0.05h}}$$

where L is the width of the structure and h is the height of the structure. Here, the natural frequency of the OB dumps is 11.55 Hz. The response spectra at the dump top surface (figure 15) show the dominant frequency range of 0–14.

Effect of phase difference across OB dumps:

One very interesting result found from the above response spectra of the OB dumps slope (figures 10 and 11 and figures 14 and 15) is that of the two sides of 200 m long dumps, one is moving up while the other is moving down. This could be explained from the following relationship [6];

$$\phi = \frac{2\pi\omega R_2}{c_s}$$

where ϕ is the phase difference (radians), ω the ground motion frequency (Hertz), R_2 the distance between two sides of the structure, and c_s the shear wave propagation velocity. According to this relationship when the phase difference across the structure is near π radian, then the above-mentioned observation could be possible. The ϕ is coming close to π radian in the present investigation due to huge length (200 m) of the OB dumps.

Critical damping fraction:

Literature prevails that if a structure undamped natural frequency and its fraction of critical damping are known, then we can model the response of the structure accurately. The natural frequency of the OB dumps having already been determined, now the critical damping fraction is tabulated from the following relationship taking the response spectra of figures 12, 13 and 16, etc.

$$\beta = \frac{1}{2\pi}\left(-\ln\frac{u_{n+1}}{u_n}\right)$$

where u_n, u_{n+1} are successive amplitudes [28]. It is found that the damping fraction is in the order of 0.041 (history response of the OB dumps at the top surface after 14 sec of seismic load), which is tallied with the average damping of the structure [7]. The fragmented rock and loose soil mixture plays the role of damping.

The average response of the vibration in the order of 0.14 m/s (shown in figures 10, 11 and 12), but being more than four times after 4 sec of seismic loading shown in figures 13 and 14 at the right-hand side dumps slope surface, develops sliding in the order of 2.8–4 m, which may be because also a sudden free oscillation gets momentum. The observation from figure 15 can also be classified in this category of sudden high peaks with sliding of 3.7 m. The resonance effect can also be responsible for these phenomena because the natural frequency of the structure in the order of 11 and the seismic spectra in the range of 0.1–15 Hz match with those particular peaks.

The OB dumps oscillate in tandem with input motion after 10 sec of seismic loading shown in figures 14, 15 and 16. The vibrations of OB dumps are merged with input motion.

9. CONCLUSION

The distinct element modeling simulates the fragmented and loose soil behaviour of the OB dumps. This is one of the novel approaches for the stability study characteristics of OB dump slopes. This method predicts well the sliding, failure surface and with a particular place of failure initiation with its visualization tools. Interpreting the sliding location will guide the field engineering to take reinforcing and/or remedial measures to stop failure at its initial stage.

These novel approaches predict well the key role of the discontinuous surface at the OB dumps mass in its stability characteristics. Here these methods surpass all the capabilities of the traditional continuum based FEM, FDM methods to model the presence of large numbers of joint planes. The heavily jointed OB dumps slope had developed cracks at the crest of the surface.

The dynamic characteristics are modeled with the present novel approaches for the OB dumps. The interpretation of the response study at many locations of the dumps slopes match well with the empirical formulae developed in continuum domain. The natural frequency, damping fraction and phase difference are explained well with this approach at seismic input motion ranges in appropriate place of history–time response curve at specified monitoring point of the OB dumps.

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