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SEISMIC SLOPE STEBILITY ANALYSIS OF JOINTED ROCK MASSES ON THE NORTHERN ABUTMENT OF GOTVAND DAM, IRAN

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ABSTRACT :

Gotvand Dam is one of the largest rockfill dams in Iran that is now under construction that the height is 178m. There is a dislocated rock mass formed of conglomerate in the right abutment of the dam which has several sets of joints and it seems to have a considerable potential of instability. A discontinuum modeling approach is to be more appropriate to analyze the problem of a rock slope with multiple joint sets which could control the mechanism of failure. In this study, the distinct element UDEC code has been used to analyze the stability of the rock mass subjected to dynamic earthquake loading. It is expected that the slope will be stable after earthquake shaking, despite of considerable sliding movements of rock layers which may take place during strong ground motion.

KEYWORDS: Rock slope, Distinct element modeling, , Earthquake, Dynamic analysis, UDEC

1. INTRODUCTION

Generally, the computation of seismic instability is based on classical limit-analyses (Janbu's method, 1973) of the corresponding static problem, to which a seismic load is applied. A well-known method is developed by Newmark (Newmark, 1965) in order to compute a finite displacement of the slope. However, the application of this technique is limited because it does not take adequate account of the dynamic behavior of the materials. In the last decade, several analytical procedures have been developed to overcome some of the limitations of this method, including the introduction of material compliance (Kramer and Smith, 1997) and post-seismic displacement calculation (Ambraseys and Srbulov, 1995).

Numerical modeling provides an alternative method to compute the real dynamic interaction between material, site geometry and wave propagation. More common are numerical analyses of dynamic slope instabilities triggered by artificial sources, such as explosions or nuclear tests (Damjanac et al., 1999). Widespread applications exist principally in the domain of static slope stability problems studied numerically by finite element (FEM), spectral element (SEM), finite difference (FDM) or distinct element modeling (DEM; Cundall, 1971). Examples include stability estimation of the Rosone landslide in the western Alps computed with FEM (Forlati et al., 2001); back-analysis of the Frank slide (Canada) with FDM (FLAC) and DEM codes (UDEC) by Benko and Stead (1998); and simulation of the Val Pola (Italy) rock avalanche with DEM (PFC2-D) carried out by Calvetti et al. (2000). However only a few applications of numerical modeling to seismic landslides can be found. Ugai et al. (1996) studied dynamic analysis of slopes by the 3-D elasto-plastic FEM (Havenith et al., 2003).

Since a rock mass is not a continuum, its behavior is dominated by discontinuities such as faults, joints and bedding planes. In general, as the presence or absence of discontinuities has a profound influence on the stability of rock slopes, the behavior of these features plays a critical rule in a stability evaluation. Several authors have used the numerical discontinuum modeling method (Cundall, 1987) to analyze slope stability problems. Among them, Easki et al., 1999 constructed a natural slope model using the above method to observe the instabilities caused by excavation near the toe of the slope. Zhang et al. (1997) have carried out studies on the dynamic behavior of a 120-m high rock slope of the Three Gorges Shiplock using the distinct element model (DEM). They found good agreement between the numerical results and the field measurements of residual displacements of rock slope during the excavation unloading stage. Heuze' et al. (1990) illustrated the usefulness of the discrete element approach for rock mass mechanical behavior analysis during wave propagation due to seismic events or rock blasting. They conclude that although continuum codes have been quite useful in simulating some ground shock effects, they are not adequate for representing dynamic block motion processes (Bhasin and Kaynia, 2004).

2. GEOLOGY OVERVIEW

2.*1. Dam Site Geology*

The Neogene sediments of the Fars Group (Gachsaran, Mishan and Aghajari Formations) outcrop in the vicinity of the dam site. They include thick evaporitic units (Gachsaran), marl, limestone and alternating sandstone, siltstone and claystone. Plio-pleistocene Bakhtyari conglomerates overlain these fine-grained sediments. The rock foundation of the dam consists of Aghajari and Bakhtyari Formations.
Figure 1 shows a geological cross-section of the dam site and also cross section of northern abutment of dam. The rock at the site comprises deposits of the Aghajari formation with interbedded claystone, siltstone and sandstone (AJn), overlain by conglomerate of the Bakhtiari formation (BKn). The sandstone and siltstone are indurated and fissured while the claystone appear as heavily over consolidated hard clay. The conglomerate is for the most part indurated and moderately strong but contains lenses and beds with poor cementation. The rock is massive in the left valley side and rises as a steep cliff some 300 m above the valley floor.

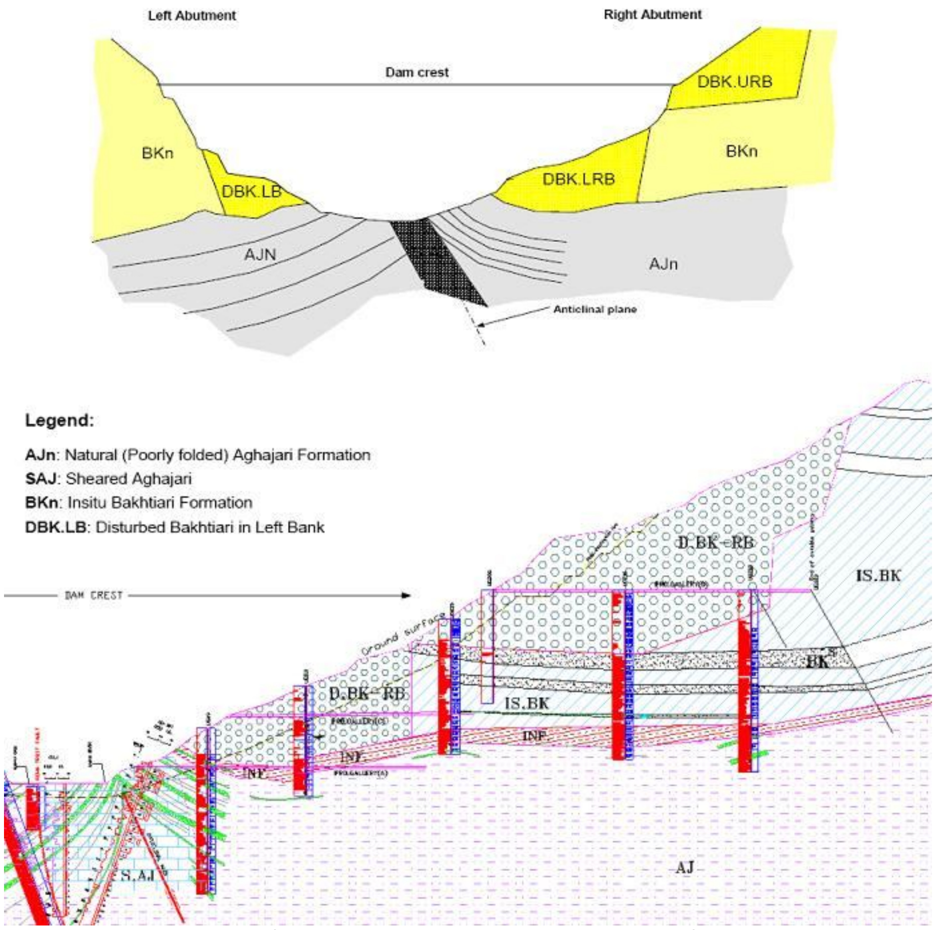

Figure 1 Schematic geological cross-section of the dam (UPPER) and Cross-section of northern abutment showing different strata and formations (LOWER)

2.1.1 Bakhtyari Formation Description

BK formation is basically formed by conglomerate. Massive conglomerate units, which can be as thick as 100 meters, are only separated by a few sandstone and claystone interlayers. Bedding planes, usually tight, are mostly marked by sandy/silty interbeds, lenses or, in some cases, by the orientation of the elongated pebbles. Pebbles of variable size, from 2 cm up to 30 cm, generally rounded to sub-rounded, are mainly limestone fragments. Chert and sandstone or siltstone pebbles are subordinate. The cement varies from calcareous to siliceous, commonly finely crystallized but sometimes with a coarser, sandy texture. Variable degree of consolidation or washout of sandy bound materials throughout the thick sequence resulted locally in loosely cemented, friable conglomerates.

2.1.2 Aghajari Formation Description

This formation is generally formed by a sequence of brown to gray calcareous sandstone with some interbeded mudstone, marlstone and some siltstones. Thin veins of gypsum are spread out in some horizons of this formation. The sedimentation of this formation is related to the river-flood plane deposits. This formation belongs to late Miocene-Pliocene and composes limey (approx-70%) and silicic (fundamentally Chert-30%) grains. The cementation is generally limy. The thickest and thinnest layers are sandstone and claystone respectively. Lateral variations in AJ formation are apparently observed when assessing the boreholes; as in lateral parts, sandstone is changed to siltstone and mudstone. In general, the dominant lithology of the station is formed by siltstone. Sandstone layers are 0.20 – 0.30 up to 5 m thick. Fine, tight lamination is the characteristic of the siltstones and siltstone/sandstone or siltstone/claystone transitions.

2.2. *Structural Geology: Upper Right Bank of Gotvand Dam*

This disturbed rock mass visible on the right bank at the location of the dam axis. This part of the right bank appears actually like it had been toppled towards the river as a whole, as evidenced by the dip direction of the bedding. Figure 2 is a photograph which illustrates this situation in the upper right bank, and where the so-called disturbed rock mass situation can be clearly seen.

About 900 measurements have been used to determine the jointing pattern at the dam site and at the appurtenant structures. These observations have been made on outcrops and in the underground workings.

Data obtained from field observations basically confirms that the E-W trending joint set (strike mainly varying between N080°E and N100°E) and the bedding planes are the main discontinuities affecting the rock foundation at the dam site. This is especially obvious in the dislocated / disturbed conglomerate units (DBK).

One set is the bedding, dipping towards south with a dip angle of 30 to 60° with 45° as a mean (set “B”). The bedding planes, with few exceptions, can be considered as tight. The second set is perpendicular to the bedding planes (which is commonly offset), dipping around 45° to the north, characterized by remarkable persistence. Spacing is between 1 to 3m. Their surfaces are generally undulating, while the small scale roughness profiles are variable, from slickenside to rough. Frequently filled with clayey and/or silty material, their width varies between a few millimeters to 30-50 centimeters (Figure 3). Shearing along these discontinuities has been mostly undertaken by the filling material. The conglomerate walls show different conditions, from saw-cut, slightly disturbed to broken matrix and, where greater displacement occurred, mylonite. Some erratic joints dipping towards north or north-east are filled with broken conglomerate in a silty clayey matrix.

3. DISTICT ELEMENT UDEC MODELING FOR SIMULATION OF DYNAMIC EVENTS IN JOINTED ROCKS

The dynamic effect of propagating seismic waves significantly increases the complexity of the slope stability problem, especially in presence of several discontinuities. Wave diffraction, reflection and focusing effects are dependent on local geological and structural conditions and make it difficult to analyze dynamic sliding mechanisms using field observations or even continuum present modeling tools in the case of jointed rock masses. As a consequence, in order to examine the influence of various structural and seismic factors on rock slope movements, it is often necessary to produce numerical models. At present, distinct element UDEC modeling, adapted both to the discontinuous character of fractured rock and heterogeneity of layered mediums and to the intact material behavior, is one of the most appropriate tools for simulation of dynamic events in jointed rocks. Using this code provides simulation of deformation mechanisms, including seismically induced bending, block tilting, and slip in rock slope stability analysis (Havenith et al., 2003).

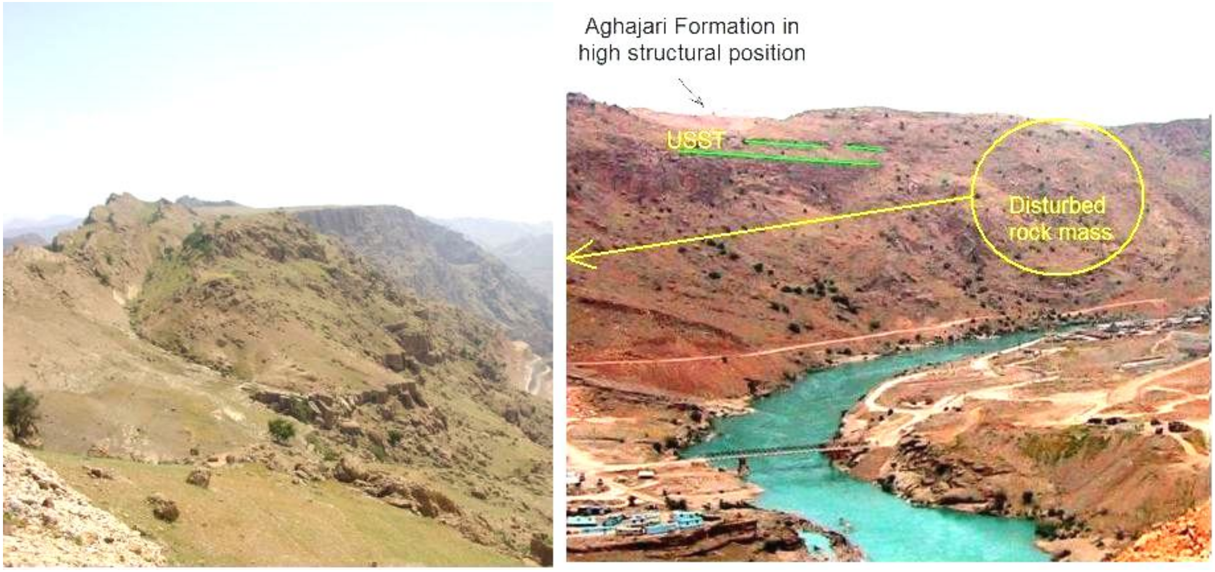

Figure 2 Right Bank, downstream view (RIGHT) and view of the upper right bank above the dam axis (LEFT).

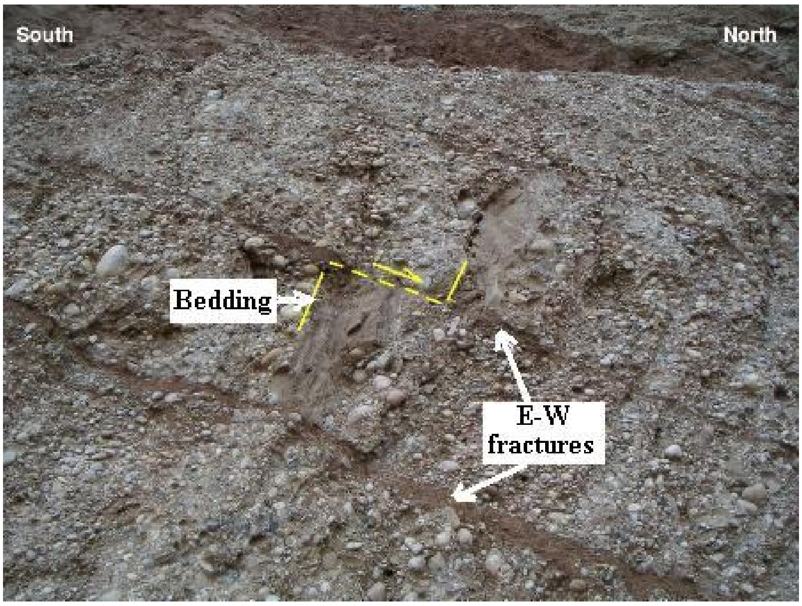

Figure 3 North dipping fractures with normal dip-slip

Up to now only few articles on dynamic UDEC simulation of rock slopes are available. Inherent complexities of dynamic analysis with UDEC and popularization of other modeling tools for slope stability problems may be a reason. However, some researchers have reported seismic analyses of jointed rocks using distinct element method. Chen et al. (1998 and 2000) analyzed the propagation of blast wave in jointed rock masses and mesh size influence on dynamic modeling using UDEC. In a similar line of thought, Zhang et al. (1997) and Wang et al. (2003) conducted some simulations. Liu et al. (2004) performed a UDEC simulation for the dynamic response of a rock slope subject to explosions (2004). Bhasin and Kaynia (2004) analyzed a high rock slope in Norway for static and dynamic stability conditions.

4.MODEL SETUP AND INPUT PARAMETERS

There are three aspects that should be considered when preparing a UDEC model for a dynamic analysis. These are: (1) dynamic loading and boundary conditions; (2) mechanical damping; and (3) wave transmission through the model. The base is assumed to be flexible, so the input velocities must be converted to stresses in order to employ the dynamic loading with a quiet boundary for the flexible foundation. The boundary stresses are then applied to the base of the model in the shear directions. Free-field boundaries are invoked along the left and right boundaries to absorb energy. Seismic loading is simulated as a input sinusoidal velocity S-wave with a peak amplitude of 0.625 m/s (acceleration of ~ 0.75 g at 2 Hz) for 12 cycles.

For a dynamic analysis, the damping in the numerical simulation should attempt to reproduce the energy losses in the natural system when subjected to dynamic loading. If an elastic (or Mohr-Coulomb) behavior is adopted for the compliance matrix, the main source of energy dissipation is contact slip, which is insufficient to reproduce the real behavior. For this reason, it is necessary to include a damping of the node velocities. Various types of damping can be used, but Rayleigh damping seems to be appropriate to dynamic problems (for detailed explanation see Bathe and Wilson, 1976). Originally, it was created for the damping of the natural oscillation modes of elastic systems, similar to the viscous attenuation, but it can also be utilized to a plastic medium. The Rayleigh damping is both proportional to the involved mass and the material stiffness and can be expressed by two factors, the critical damping ratio, ξ, and the angular frequency, f (Havenith et al. 2003). Rayleigh damping is frequency-dependent but has a “flat” region that spans about a 3:1 frequency range, as shown in Figure 4 that shows the variation of the normalized critical damping ratio with angular frequency, ω_i . Three curves are given: mass and stiffness components only and the sum of both components. The curve representing the sum of both components reaches to a minimum corresponding to $f_{\min}$ and $\xi_{\min}$.

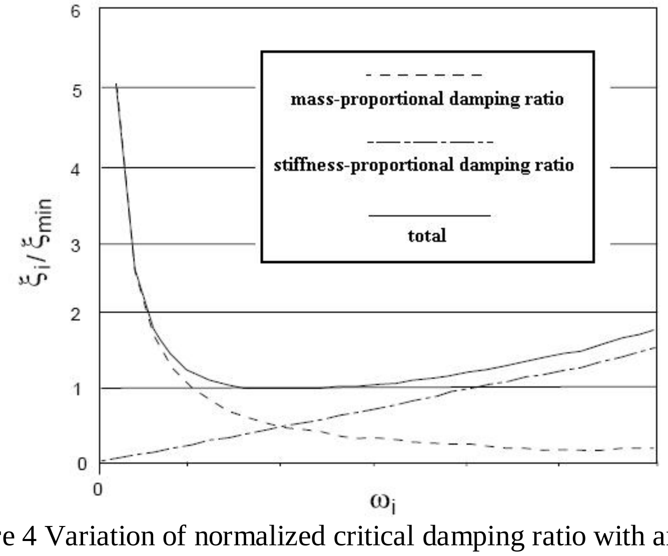

Figure 4 Variation of normalized critical damping ratio with angular frequency

The idea in dynamic analysis is to adjust $f_{\min}$ of the Rayleigh damping so that coincides with the range of predominant frequencies in the problem. $\xi_{\min}$ is adjusted to coincide with the correct physical damping ratio. The “predominant frequencies” are neither the input frequencies nor the natural modes of the system, but a combination of both. For many problems, the predominant frequencies are related to the natural mode of oscillation of the system. Examples of this type of problem include seismic analysis of surface structures such as dams or dynamic analysis of underground excavations. (Itasca, 2004)

Natural frequency of the model may be inferred by running the model with high strength properties and no damping, and monitoring the velocity history at different locations in the model. Velocity histories recorded at such model indicates an approximately 2 Hz natural frequency for non-damping model.

For geological materials (e.g. soils), damping commonly falls in the range of 2 to 5% of critical (Biggs 1964). So the critical damping ratio for this problem has been assumed equals to 5%.

In order to allow waves at the input frequency to propagate accurately in the model, the zone size should be sufficiently small. The maximum zone size derived by consideration of wavelength of peak velocities and joint characteristics. So for the current case, it can be shown that a 30m maximum zone size is sufficiently small to simulate wave propagation accurately. Note that block dimension of disturbed Bakhtyari region in the model is less than 2 m and therefore, wave propagation will be accurately performed through the model.

Table 1 has listed the rock material properties utilized in UDEC model. Also table 2 has presented discontinuity properties used in UDEC model. It may be noted that for UDEC model of the problem, the surface region of DBK has divided into two joint sets with average 2m spacing. But for the underlying DBK and BKn region, the spacing gradually increases to save computational time.

Table 1 Rock material properties utilized for distinct element UDEC modeling

region	Density (ton/m^3)	Bulk modulus (GPa)	Shear modulus (GPa)	Cohesion (kPa)	Friction angle (deg)	Tensile strength (kPa)
D.BK (intact rock)	2.300	7.816	5.620	10,000	50	7,300
BK_n (rock mass)	2.480	4.000	2.400	500	52	2,140

Table 2 Discontinuity properties utilized for distinct element UDEC modeling

Discontinuity	Jkn (GPa/m)	Jks (GPa/m)	Cohesion (kPa)	Friction angle (deg)	Dip (deg)	Spacing (m)
Joint set 1	6.80	1.70	0	20	315	1-3
bedding	5.20	1.30	0	30	45	1-3

5. MODELING PROCEDURE AND RESULTS

Dynamic simulation of earthquake occurring for the current case has been performed by several successive states in UDEC calculations. By running the first state, model has reached to primary equilibrium adjusting strength parameters of joints and materials at high values. Then model has been conducted to apply real joint properties until equilibrium condition. Excavation of dam foundation and slope surface has simulated in the next state. After integration of free-field and viscous boundary conditions in bottom and lateral boundaries, respectively and conducting of unbalanced forces to a low amount indicating equilibrium of the state, dynamic state has been developed by applying shear wave to bottom of the slope.

For monitoring of dynamic response of the model during and after seismic loading, several points at different locations of the slope are selected. Figure 5 illustrates the velocity and displacement histories recorded at two surface monitoring points, during model time. The first 6 seconds refers to seismic sinusoidal loading.

Displacement histories indicate that earthquake loading causes sliding of layers downward due to strong shaking of blocks. Horizontal displacement of point 1 and 2 after seismic loading are 2.94 m and 4.19 m leftward respectively. Also vertical displacement of point 1 and 2 are 2.16 m and 0.93 m downward. These values are relatively large and in many cases may cause instability conditions. But referring to huge scale of slope and because these movements stop rapidly after seismic loading, they can not be judged as instability indicators. Indeed movement of layers could be expected while shaking, but geometry of slope discontinuities and strata will prevent movements to continue and therefore, the slope has a general stable state despite of large deformations.

6. CONCLUSION

This paper presented a dynamic distinct element modeling of northern rock slope abutment of Gotvand dam, located in Iran. Dynamic simulation has been performed through several successive stages which model the static equilibrium state, excavation of dam foundation and application of seismic inputs. Results indicate that the slope can tolerate simulated seismic conditions in spite of significant deformations. Because of major influence of discontinuity geometry in this case, especially at the surface regions, it should be advised that a more completed survey of joint sets in the surface regions may be indispensable.

The main conclusion is that dynamic modeling of jointed rock masses may endure even strong dynamic events due to their structurally flexibility caused by discontinuities. Indeed the discontinuous nature of jointed rock slopes may play two adverse roles in stability conditions. Separation and movement of layers can form an instable region or adversely terminate in energy dissipation resulting of discontinuity sliding and block motion.

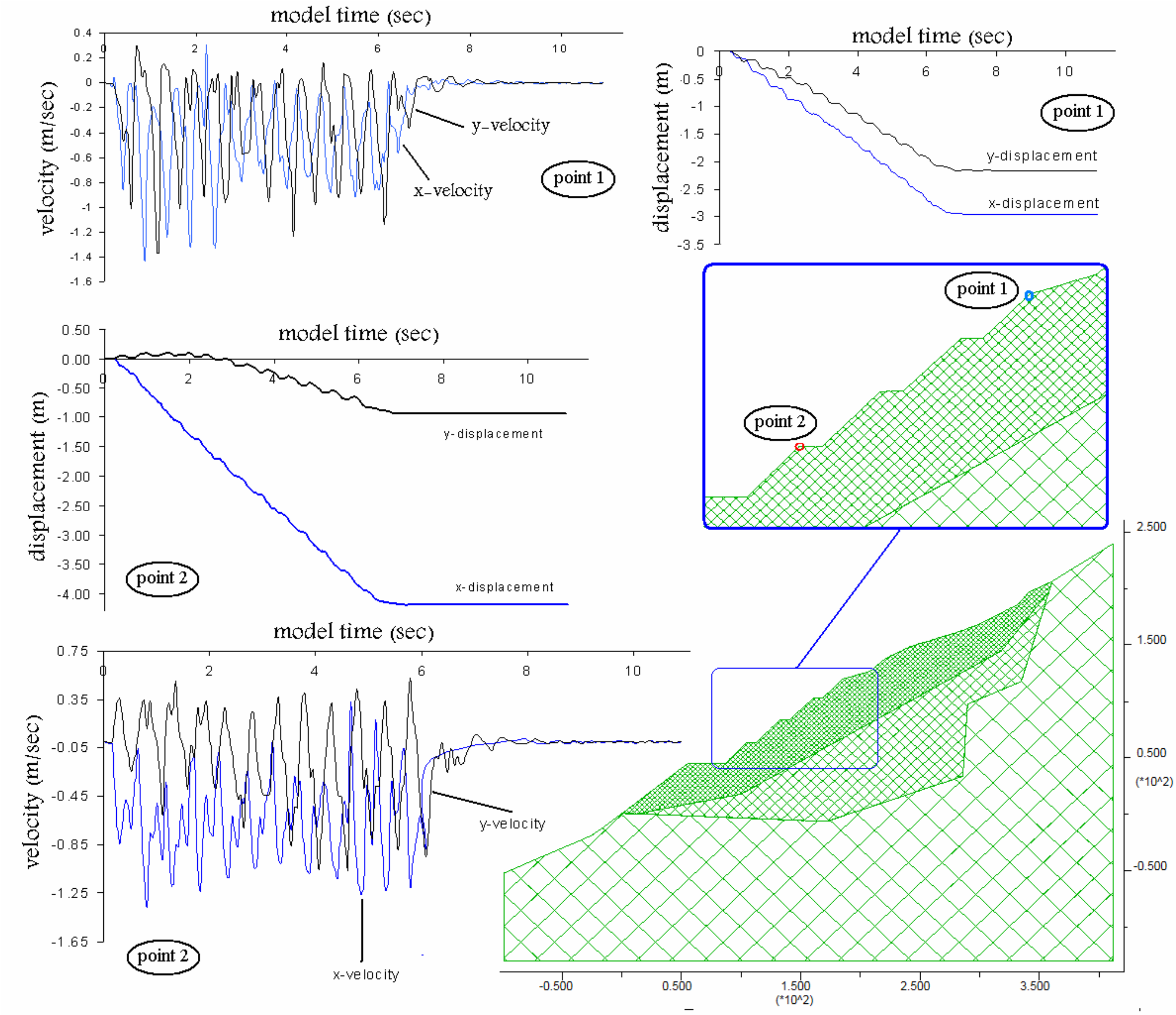

Figure 5 Illustration of distinct element UDEC model and recorded histories.

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