REALISTIC DYNAMIC ANALYSIS OF JOINTED ROCK SLOPES USING DDA

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Geological and Seismological Setting...
Seismicity along the Dead Sea Rift System

4.0 < ML < 4.9
5.0 < ML < 5.9
6.0 < ML
Topographic Site Effect in Masada

Spectral amplification of ground motions
(Zaslavsky and Shapira, 2000)
Typical Failure Modes

King Herod Palace: combined sliding (East face) and toppling (West Face) leading to deterioration of entire slope segments

Snake Path Cliff: sliding, and “block slumping”, of large, removable key blocks + time dependent propagation of tensile cracks
Rock Mechanics Considerations...
Mechanical Properties of Intact Rock

- Uniaxial Compressive Strength of intact Dolomite $\sigma_c > 300$ MPa;
- Elastic Modulus $E = 43$ GPa
- Poisson’s Ratio $\nu = 0.18$
Shear Strength of Bedding Planes

An example of a natural, filled, bedding plane in Masada dolomites

\[ \phi_{\text{saw-cut}} = 28^\circ \]
\[ \phi_{\text{residual}} = 23^\circ \]

Determination of residual friction angle using tilt tests on “saw cut”, and “ground” surfaces
Triaxial Tests of Inclined, Filled, Saw-Cut

\[ \sigma_3 = 16.2 \text{ MPa} \]

\[ c = 0 \text{ MPa} \]

\[ \phi = 22.7^\circ \]
Direct Shear Tests of Natural Bedding Planes
Direct Shear Tests for Rough Bedding Planes

$\phi_{\text{peak}} = 41^\circ$

$\phi_{\text{residual}} = 23^\circ$
Summary: Mechanical Properties of Rock Mass

- Strength of intact rock > 300 MPa
- Elastic modulus = 43 GPa
- Poisson’s ratio = 0.18
- Peak friction angle of bedding planes = 41°
- Residual friction angle of bedding planes = 23°
Measured keyblock Displacements...
Joint Displacement Monitoring Devices

Flat Jack

LVDT based “Joint Meter”
Block 3 – the “control” block
Joint Meter Output - Block 3

Relative Displacement

Flatjack Pressure

JM = Joint Meter (LVDT)
FJ = Flat Jack

JM10
JM11
FJ3
Joint meter output - Blocks 1, 2, 3

Gulf of Eilat Seismicity???
April 7, 98: M=4.4
April 10, 98: M = 4.3
Influence of climatic fluctuations– Block 3

 JM = Joint Meter (LVDT)
 T = Thermoresistor
 RH = Relative Humidity
The monitored keyblocks exhibit dynamic behavior

Periodic keyblock displacements with amplitude of up to 1mm and period of 6 months – most likely climatically controlled

High keyblock sensitivity – most likely due to limiting state of static equilibrium
Limit Equilibrium Analysis...
Representative Keyblock in the East Face (Block 1)

Plan view of Block 1

$H = 15m$

$\alpha = 20^\circ$

$\psi$

$\sigma$

$V$

$W$

$U$

$A$

$A'$

$J1$

$J2$

$J3$

$5 m$

$DDATUM, Zw = 0$
Influence of Water Head in “Tension Crack” on Factor of Safety Against Sliding and Rotation – Block 1

\[ \phi_{\text{available}} = 22.7^\circ \]
True Geometry of Block 1

Bp: 00011
Spacing Dimensioned Block
Volume: 553.488

Mass: 1.52136e+106
Unsupported FOS: 1.15623
Unsupported Mode: bedding

<table>
<thead>
<tr>
<th>Plane</th>
<th>Dip/Dip Dir.</th>
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<tbody>
<tr>
<td>Bedding</td>
<td>201/24</td>
</tr>
<tr>
<td>J2</td>
<td>84/07</td>
</tr>
<tr>
<td>J3</td>
<td>75/52</td>
</tr>
<tr>
<td>F1</td>
<td>64/60</td>
</tr>
<tr>
<td>F2</td>
<td>901/26</td>
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<tr>
<td>TOP</td>
<td>0/0</td>
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</table>
Elements of 3D Graphical Solution

Static Solution

Pseudo - Static Solution
Total Required Support Force (Ton) for Block 1

FACTOR OF SAFETY = 1.5

Saturated Case

Dry Case
Summary: Limit Equilibrium Analysis

• *Fully three dimensional analysis is required when stability of individual, prismatic, keyblocks is of concern.*

• *Dominant failure mode in east slope of mountain is block sliding*

• *Relatively small water head will induce sliding of critical keyblocks*
Support Installation…

Support installation in progress

Preparations for support installation
Horizontal Drilling
The Final “Product” in the Snake Path Cliff
Fully Dynamic DDA...
Upper Terrace of King Herod’s Palace
Joint Trace Map Generation…
Joint Spacing and Orientation – North Palace

**Joint Length (m)**
- $N = 100$
- Mean = 2.7m

**Bed Spacing (m)**
- $N = 59$
- Mean = 60cm

**J2 Spacing (cm)**
- $N = 80$
- Mean = 14 cm

**J3 Spacing (cm)**
- $N = 69$
- Mean = 16.8 cm

![Diagram showing joint orientation and spacing](image)
A Synthetic Joint Trace Map Model
A Photo-geological Discontinuity Trace Map
DC Realization of Digitized Photo-geological Map
Discontinuous Deformation Analysis (Shi, 1993)

- A Discrete Element Method (Completely Discontinuous)
- A Rigorous Contact Detection Algorithm
- Normal and Shear Springs at Contact Points Between Blocks
- No Tension / No Penetration Between Blocks
- Sliding Deformation Modeled Using Coulomb’s Law
- Solution for Displacement Obtained by Minimization of Total Potential Energy (as in FEM).
- Solution Progresses by a Time-Step Marching Scheme
- First Order Displacement Approximation
- Simply Deformable Blocks
DDA Validation…
Block on an Incline:
Gravitational Loading - Constant Acceleration

(MacLaughlin and Sitar, 1997)
Block on an Incline – Dynamic Loading
(Hatzor and Feintuch, 2001)

\[ a(t) = 2\sin t + 3\sin 2t \]

Graph showing acceleration, velocity, and displacement over time.
Shaking Table Experiments
(Wartman, 1999)

![Shaking Table Experiment Setup](image)

<table>
<thead>
<tr>
<th>No.</th>
<th>Instrument</th>
<th>Direction of Measurement</th>
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<tbody>
<tr>
<td>1</td>
<td>accelerometer</td>
<td>parallel to plane</td>
</tr>
<tr>
<td>2</td>
<td>accelerometer</td>
<td>parallel to plane</td>
</tr>
<tr>
<td>3</td>
<td>accelerometer</td>
<td>horizontal</td>
</tr>
<tr>
<td>4</td>
<td>displacement transducer</td>
<td>horizontal</td>
</tr>
<tr>
<td>5</td>
<td>displacement transducer</td>
<td>parallel to plane</td>
</tr>
</tbody>
</table>
Comparison Between Shaking Table and DDA

(Tsesarsky, Hatzor, and Sitar 2002)

\[ a_y(\phi = 16^\circ) = 0.08g \]

\[ t_y(\phi = 16^\circ) = 0.64 \text{ sec} \]

- Measured
- \( k_01 = 1 \)
- \( k_01 = 0.985 \)
- \( k_01 = 0.98 \)
- \( k_01 = 0.975 \)
- \( K_01 = 0.95 \)
Summary: Validation Study

• Good agreement between numeric and analytical solutions - provided that the control parameters \((g_01, g_02)\) are optimized in constant acceleration cases.

• Similar results are found for time dependent acceleration.

• When comparing time dependent acceleration analysis with physical models (e.g. shaking table) some velocity damping must be introduced in order to get good agreement. For a single block problem the optimal value of velocity damping seems to be not greater than 2%. 
The Real Case...
The Nueiba 7.1 Earthquake of Nov. 1995
Fill Response (Eilat)

Vertical

N-S

E - W

Time (sec)

Accl. (g)

0 10 20 30 40 50 60
De-convolution: Bed-Rock Response
(Zaslavski, Shapira, and Arzi, 2000)
Convolution: Topographic Site Effect

![Graph showing acceleration over time for N-S and E-W directions.](image)
Predicted Damage by DDA

No Energy Damping

2.5% Kinetic Damping

5% Kinetic Damping
Rock Bolt Reinforcement:
Modified Record Normalized to a 0.6g PGA

Dense Bolting Pattern: $L = 6m, s = 2m$
Sparse Bolting Pattern: $L = 6m, s = 4m$
• The DDA method can be used to perform a fully dynamic analysis of a jointed rock slope.

• Historical evidence indicate that the modeled slope has sustained at least 4 episodes of PGA = 0.2g earthquakes in the past.

• This historical evidence is confirmed by DDA.

• DDA with no energy dissipation clearly over predicts damage due to shaking.

• On the basis of historical performance we believe that a reasonable damping value for a multi block problem in DDA should be in the order of 2%.