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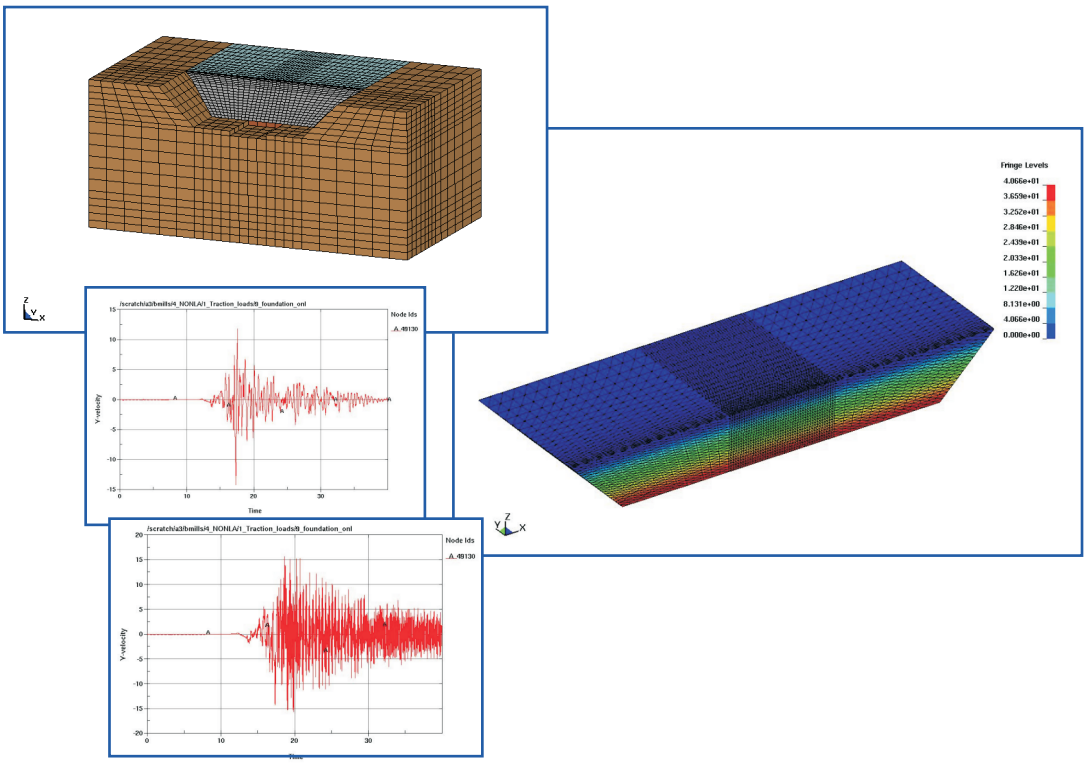
Report DSO-08-02

Nonlinear Analysis Research



Dam Safety Technology Development Program

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Denver, Colorado

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Denver, Colorado

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Mission Statements

The mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to Indian Tribes and our commitments to island communities.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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Effect of Hourglassing Control in LS-DYNA for Static Loads

To study the effects of hourglassing parameters particular to LS-DYNA, a finite element model was generated and analyzed for static loading conditions. A number of internal variables within the program were determined to be likely key players in the hourglassing behavior of the model and were varied to determine their effects on the model as a whole, as well as the individual materials of which the model was composed.

Background

The explicit part of LS-DYNA is an effective and efficient method for seismic, blast, and nonlinear analyses. Explicit analyses use simple 8-noded solids with single integration points. This allows for fast integrations through the elements.

The issue of hourglass modes is best described by the following text taken from the LS-DYNA theory manual:

> The biggest disadvantage to single-point integration is the need to control the ***zero energy modes*** which can arise, known as hourglassing modes. Undesirable hourglass modes tend to have periods that are typically much shorter than the periods of the structural response, and they are often observed to be oscillatory. However, hourglass modes that have periods that are comparable to the structural response periods may be a stable kinematic component of the global deformation modes and must be admissible. One way of resisting undesirable hourglassing is with a viscous damping or small elastic stiffness capable of stopping the formation of the anomalous modes but having a negligible effect on the stable global modes.

Since hourglass deformation modes are orthogonal to the strain calculations, work done by the hourglass resistance is neglected in the energy equation. This may lead to a slight loss of energy; however, hourglass control is always recommended for the underintegrated solid elements. The energy dissipated by the hourglass forces reacting against the formations of the hourglass modes is tracked and reported in the output files MATSUM and GLSTAT.

In assessing hourglassing in LS-DYNA, it is helpful to know how internal energy within the model is calculated. Internal energy and hourglassing energy should be compared to ensure that the model is functioning properly with respect to hourglassing modes.

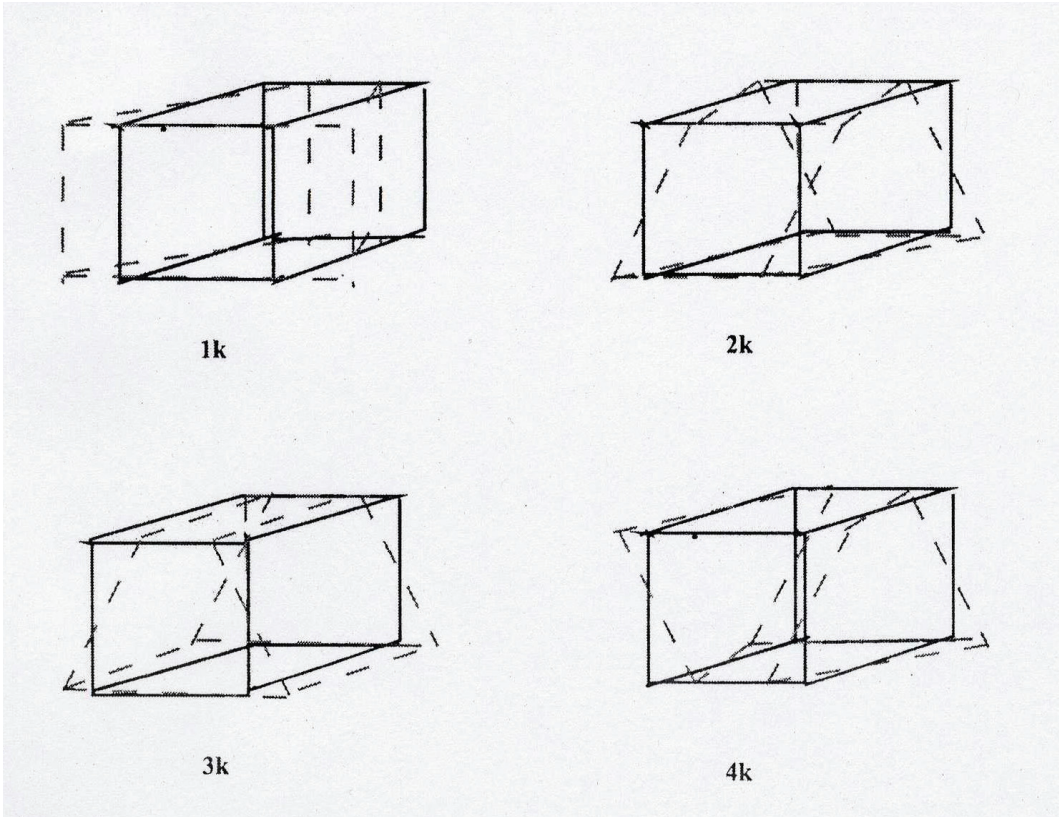


Figure 1.—Hourglass modes of an 8-node element with one integration point. Twelve modes exist (Flanagan and Belytschko, 1981) (taken from *LS-DYNA Theory Manual* [Livermore Software Technology Corporation, 2006]).

LS-DYNA operates on the six components of stress and strain (tensorial values) when computing internal energy. The calculation of internal energy (IE) is done incrementally for each element as follows:

> (IE) new = (IE) old + sum over all six directions of (stress * incremental strain * volume)

The internal energies of all the elements are summed to give the total internal energy. Additionally, energy dissipated due to stiffness damping (keyword card *DAMPING_PART_STIFFNESS) is added to the internal energy if RYLEN = 2 in keyword card *CONTROL_ENERGY (Rayleigh energy computed).

Material Properties

The following material properties were used in the model.

Modulus of Elasticity

A modulus of elasticity of 5,750,000 lb/in^2 was used for both the dam and the foundation.

In the report *State-of-Practice for the Nonlinear analysis of Concrete Dams at the Bureau of Reclamation* (January 2006), a series of graphs document the modulus of elasticity in different Reclamation dams. The average static modulus of elasticity (fig. 4.11 in the report) is given as 3,670,000 lb/in^2, and the average dynamic modulus of elasticity is given as 4,070,000 lb/in^2 (fig. 4.15 in the report). Visual inspection of the plots, however, shows a reasonable number of values equal to or greater than the value used for this analysis. Considering this, a modulus of elasticity of 5,750,000 lb/in^2 is a reasonable value.

Density

A density of 150 lb/ft^3 was used for the concrete dam. A density of 165 lb/ft^3 was used for the foundation and rock block.

Static Coefficients of Friction

The foundation-to-dam contact surface was a TIED_SURFACE_TO_SURFACE type with a static coefficient of friction of 0.57 for all analyses except 6 and 6.1.

For analyses 6 and 6.1, the foundation-to-dam contact surface was an AUTOMATIC_SURFACE_TO_SURFACE_TIEBREAK with a static coefficient of friction of 0.57 and normal and shear failure stress values of 1E10.

The dam contraction joints were AUTOMATIC_SURFACE_TO_SURFACE_ TIEBREAK types with a static coefficient of friction of 0.5 for all analyses and normal and shear failure stress values of 0.0.

For all analyses, the master surface was on the foundation, and the slave surface was on the dam.

Poisson's Ratio

Dam and foundation materials both were assigned a Poisson's ratio of 0.20.

Damping

Rayleigh damping, a, was applied during the analyses. A value of a = 1.8 was used during the 3 seconds used for application of static loads. During the next three seconds of quiet time, the value was reduced to a = 0.5. The plots on figure 2 show the percent critical damping related to these two values. The percent critical damping is less than 5 percent for frequencies greater than or equal to 3 Hz for a = 1.8 and less than 1 percent damping for a = 0.5.

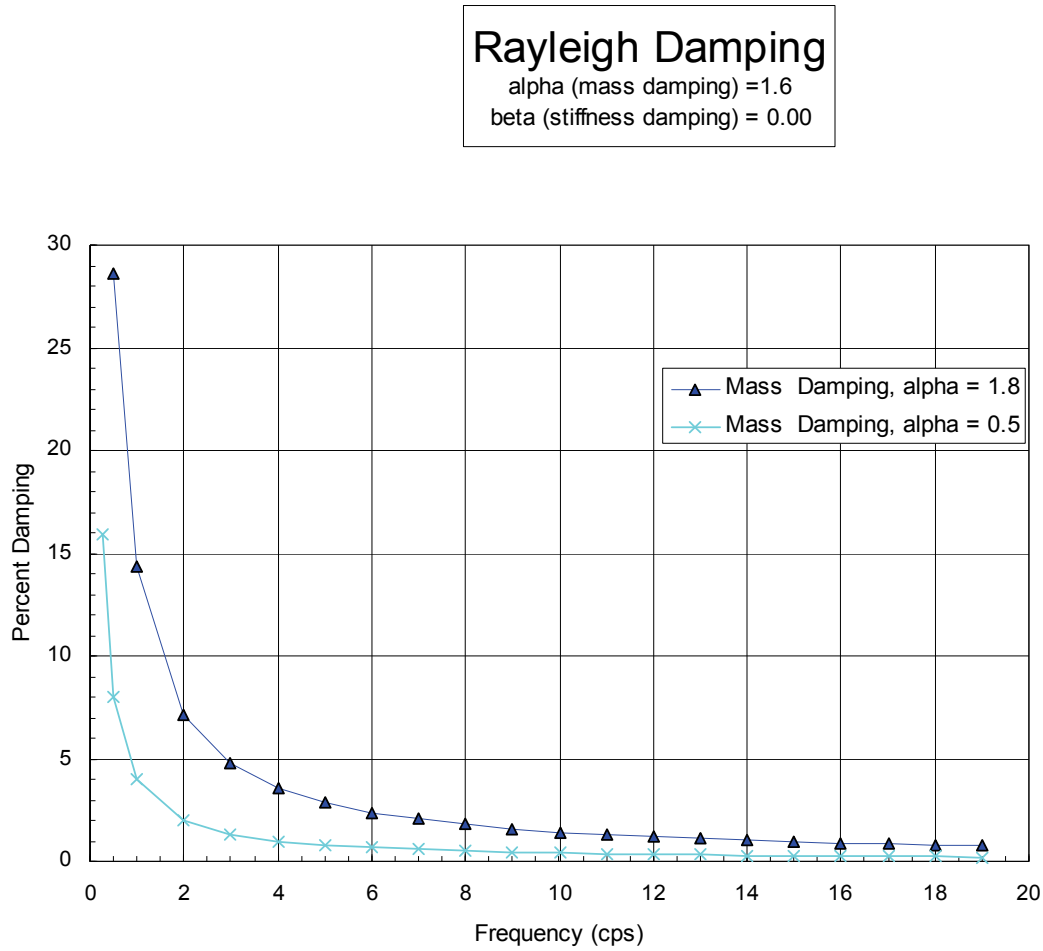


Figure 2.—Rayleigh damping.

Contact Surface Properties

Table 1 lists the properties of the contact surfaces used for all model analyses in this study.

Static Loads

Gravity was applied for 3 seconds and was allowed to stabilize over the next 3 seconds. At the end of the gravity application, the weight of the dam and static water pressure induced stresses representative of real world conditions in the dam and foundation.

Model

The finite element model used for this study (fig. 3) was a simplified representation of Elephant Butte Dam in New Mexico. The dam modeled had a

Table 1.—Contact surface properties

Contact surface	Property
Water to foundation	**Type—**SURFACE_TO_SURFACE All variables set to default values.
Dam to water	**Type—**SURFACE_TO_SURFACE All variables set to default values.
Foundation to dam	**Type—**TIED_SURFACE TO SURFACE All variables set to default values, except: Static coefficient of friction = 0.57
Foundation to dam (analyses 6 and 6.1)	**Type—**AUTOMATIC_SURFACE_TO_SURFACE_TIEBREAK All variables set to default values, except: Static coefficient of friction = 0.57 Tiebreak active Normal failure stress = 1E10 Shear failure stress = 1E10 Ignore shell thickness offsets
Rock to foundation	**Type—**AUTOMATIC_SURFACE_TO_SURFACE_TIEBREAK All variables set to default values, except: Static coefficient of friction = 0.0 Tiebreak active (failure stresses = 0)
Contraction joints	**Type—**AUTOMATIC_SURFACE_TO_SURFACE_TIEBREAK All variables set to default values, except: Static coefficient of friction = 0.5 Tiebreak active (failure stresses = 0)

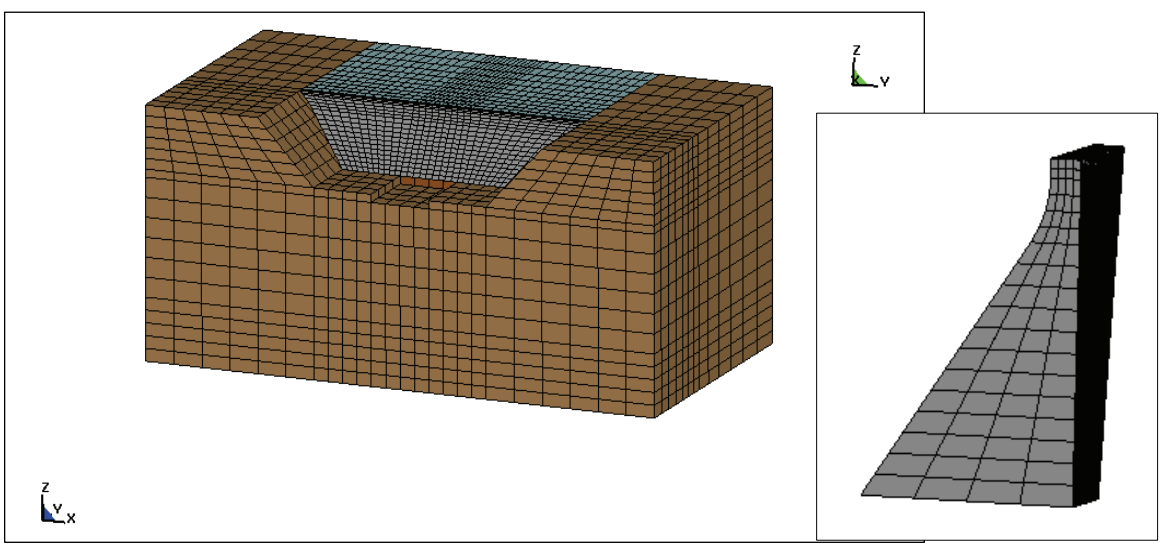


Figure 3.—The LS-DYNA model used in hourglassing study.

cross section identical to Elephant Butte Dam's cross section above elevation 4215, making it 195 feet tall. A rock block below the middle section of the dam was modeled as a flat, rectangular piece of the same material as the foundation. The dimensions of the rock block in X (cross-canyon), Y (upstream-downstream) and Z (vertical) were 200 feet, 127 feet and 27 feet, respectively.

The foundation extents complied with Reclamation's (2006) recommended dimensions. The upstream-to-downstream and cross-canyon dimensions were twice the vertical dimension.

Analysis Overview and Procedures

For this project, six different model parameters were varied to determine their impact on hourglassing. Five of these parameter changes are shown in table 2. The sixth change was a contact surface change for analyses 6 and 6.1 in which a high tiebreak value was applied to the contact surface between the dam and the foundation. Contact surface characteristics are covered in more detail later in this report.

Table 2.—Model parameter changes

Model No.	IHQ (dam and foundation)	IHQ (water)	QM (dam and foundation)	QM (water)	Foundation/dam relative mesh size
1	5	5	0.05	0.05	fine/coarse
1a	3	3	0.05	0.05	fine/coarse
2	5	5	0.1	0.1	fine/coarse
2a	3	3	0.1	0.1	fine/coarse
3	5	5	0.15	0.15	fine/coarse
3a	3	3	0.15	0.15	fine/coarse
4	5	5	0.1	0.1	coarse/fine
4.1	5	1	0.1	0.0001	coarse/fine
5	5	5	0.1	0.1	fine/fine
5.1	5	1	0.1	0.0001	fine/fine
6	5	5	0.1	0.1	fine/coarse
6.1	5	1	0.1	0.0001	fine/coarse

IHQ = hourglass control type:

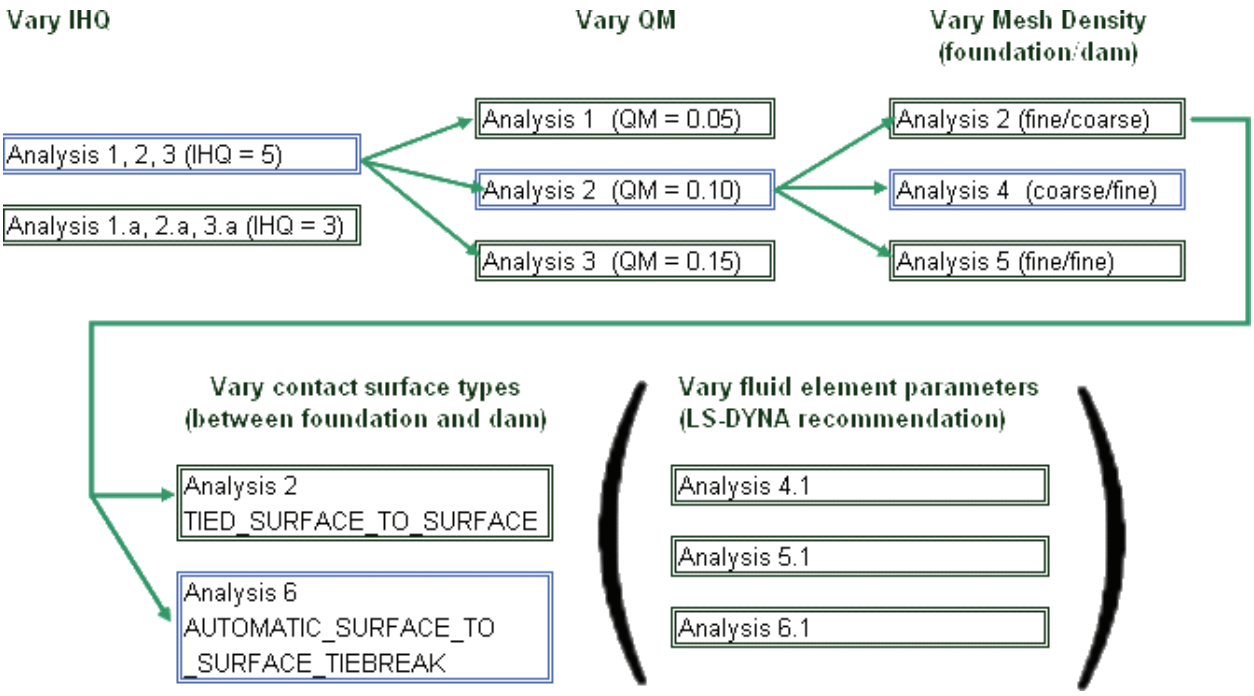
- IHQ = 3 (Flanagan-Belytschko viscous form)
- IHQ = 5 (Flanagan-Belytschko stiffness form) (typical Reclamation)
- IHQ = 1 (standard LS-DYNA viscous form)

QM = hourglass coefficient:

- Varied between an assumed lower limit (for IHQ = 3 or 5) of 0.05 and an upper limit (given in the LS-DYNA keyword manual [Livermore Software Technology Corporation, 2006]) of 0.10.

The procedure for the analyses was ordered as shown in table 3.

Table 3.—Procedure for analyses



Three variables within the *HOURGLASSING card that were specifically not varied during the course of these analyses are IBQ, Q1 and Q2, the so-called "bulk viscosity" parameters. Bulk viscosity is used to treat shock waves within an LS-DYNA model. The default values for Q1 and Q2 may be changed globally via the *CONTROL_BULK_VISCOSITY card, although LS-DYNA recommends leaving bulk viscosity parameters at their default values. It is not anticipated that any change in bulk viscosity defaults, or even turning off bulk viscosity altogether, would have a significant effect on the results for seismic or quasi-static loading.

Static Results

The results and effects of various changes within the model and the subsequent analyses of these changes are summarized here. Each section describes a single change to the model and the effect generated on the results.

Hourglass Control Type (IHQ)

Types of hourglass control were modeled:

- Stiffness hourglassing control (analyses 1, 2, 3) (typical Reclamation)
- Viscous hourglassing control (analyses 1.a, 2.a, 3.a)

There are two main types of hourglassing control. LS-DYNA provides eight different options within these two types, depending on the application. The Bureau of Reclamation typically has used a stiffness hourglassing control type identified in LS-DYNA as IHQ = 5, known as *Flanagan-Belytschko stiffness form with exact volume integration* for solid elements for all materials in a model. The first series of analyses examined the effects of using IHQ = 3, known as *Flanagan-Belytschko viscous form with exact volume integration* for all the materials in the model instead of IHQ = 5. The hourglassing control type for the fluid elements was also changed in three of the analyses. This will be discussed in a later section of this report. Besides IHQ = 3 and IHQ = 5, LS-DYNA provides six other options for hourglassing control type. These other options were not modeled during this analysis.

In general, it is recommended that viscous hourglass control types (IHQ) be used for "problems deforming with high velocities." Stiffness hourglassing control types are "preferable for lower velocities, especially if the number of time steps is large" (Livermore Software Technology Corporation, 2003).

Both stiffness hourglassing control and viscous hourglassing control were modeled. The results generated using the viscous form of hourglassing control for all materials (analyses 1.a, 2.a, and 3.a) showed significant changes in the analysis results when compared to analyses run using the stiffness form. A summary of the observed changes in the model is given here.

Effect on Hourglassing Energy

Hourglassing energy was seen to increase steadily over the entire static run time (6 seconds) when using viscous hourglassing control (IHQ = 3) (see appendix A, figures 3a, 5a, and 7a.) When using stiffness hourglassing control (IHQ = 5), the hourglassing energy did not display this same increase of hourglassing energy over the entire 6 seconds of run time, but instead leveled off at 3 seconds (see appendix A, figures 2a, 4a and 6a).

Effect on stresses

Stress plots for analyses run with stiffness hourglassing control (IHQ = 5) (see appendix A, figures 2, 4, and 6 "g" and "h") displayed more chatter than plots generated from the analyses that were run with viscous hourglass control (IHQ = 3) (see appendix A, figures 3, 5, and 7 "g" and "h").

Because of the observed differences between viscous and stiffness hourglassing control, as well as the specification in the keyword manual cited above (Livermore Software Technology Corporation, 2003), that viscous hourglassing

control is generally for the purpose of high velocity deformations (presumably blast-type loading—at least an order of magnitude faster than earthquake loading); further study into the effect of changing this parameter (IHQ) for the dam and foundation was not pursued, and stiffness hourglassing control (IHQ = 5) was specified for the remaining analyses (4, 4.1, 5, 5.1, 6, 6.1). Except as discussed later in this report (under *LS-DYNA Recommendation*), IHQ = 5 was used for all subsequent analyses and is recommended for future static and seismic modeling of dams and foundations.

Hourglass Coefficient (QM)

Effect on hourglassing energy

Global and material hourglassing energy plots (from *GLSTAT and *MATSUM) showed slight decreases in hourglassing energy for higher values of QM in analyses 1, 2 and 3 (see appendix A, figures 2a, 4a, and 6a).

Effect on stresses

Also in analyses 1, 2, and 3, principal and shear stresses were observed to decrease somewhat within the dam and remain about the same in the foundation and rock block for increasing values of QM. (see appendix A, figures 2, 4, and 6 “g” and “h”). Stresses in two elements across the contact surface were compared. (see fig. 4.) Variations in stress were generally less than 10 percent.

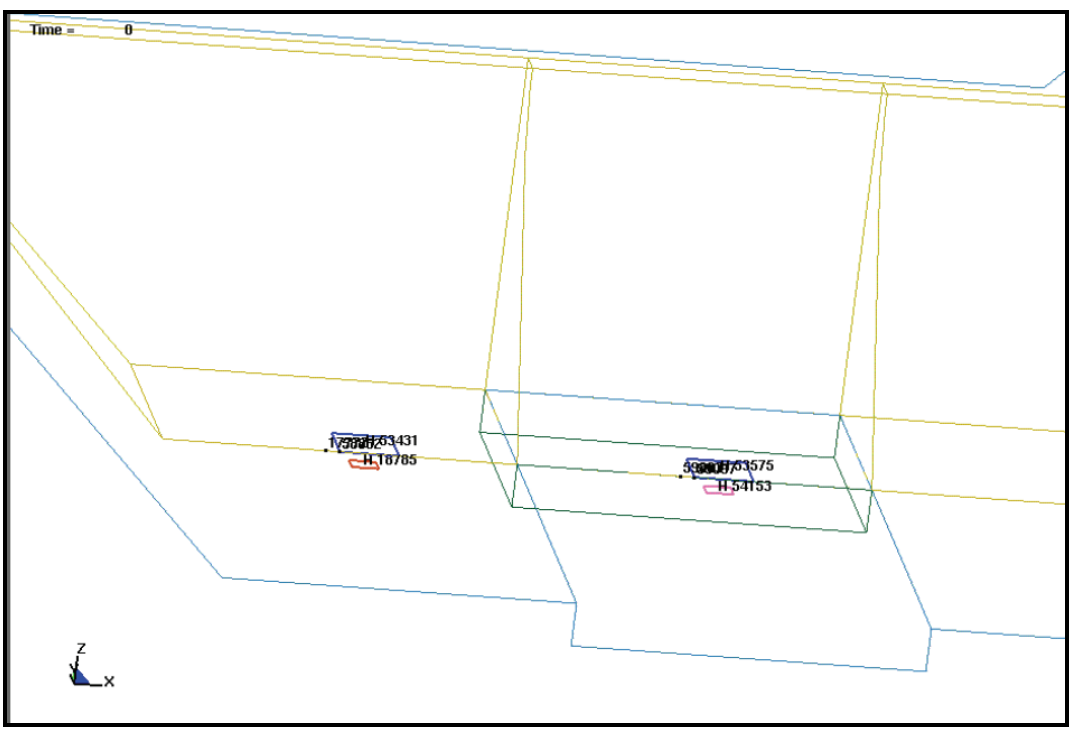


Figure 4.—Dam and foundation and rock block elements for stress comparison (approximate for varying mesh size ratios).

Variation of QM was analyzed in this first set of analyses. Analysis 2 (with a QM value of 0.10) served as the baseline for subsequent analyses. QM = 0.10 is recommended for future static and seismic modeling of dams and foundations.

Mesh Size Ratios (Foundation/Dam)

Table 4.—Parameter change

Analysis numbers	Mesh characteristics (relative to each other)
1, 1a, 2, 2a, 3, 3a, 6, 6.1	Fine foundation mesh (ratio of 2/1) Coarse dam mesh
4, 4.1	Coarse foundation mesh Fine dam mesh (ratio of 2/1)
5, 5.1	Fine foundation mesh (same as 1, 1a, 2, 2a, 3, 3a and 6) Fine dam mesh (same as 4 and 4.1) (ratio of 1/1)

The master/slave relationships for the contact surfaces in all the analyses are:

Rock block = slave
Foundation = master

Dam = slave
Rock block = master

Dam = slave
Foundation = master

Analysis 2 and analysis 4 are identical except that they have different foundation/ dam mesh density ratios (analysis 2—fine/coarse, analysis 3—coarse/ fine. See table 2). Analysis 2 exhibits hourglassing behavior under application and settling of static load visible at 1,000 times magnification. This is especially apparent along the rock-block-to-dam and foundation-to-dam contacts at the center of the dam. The foundation and rock block appear to be experiencing hourglassing while the dam is not. The foundation experiences hourglassing along the slot where the rock block sits. Analysis 4 exhibits virtually no visible hourglassing behavior under application and settling of load, even at 2,000 times magnification. Observation of figures 4 and 8 “a” in appendix A shows that hourglassing energy in the foundation increased by nearly a factor of three from analysis 4 to analysis 2. The hourglassing energy in the rock block increased by a factor of about 10. (see appendix A, figures 4a, and 8a.)

Analysis 5, which has a fine mesh throughout, exhibited a small amount of visible hourglassing at 1,000 times magnification. As with analysis 4, this behavior takes place at the center of the dam, primarily on the rock-block-to-dam contact. A small amount of hourglassing takes place at the dam-to-foundation contact along the slot where the rock block sits. As with analyses 2 and 4, hourglassing

behavior could only be observed in the foundation and rock block. The dam did not appear to be undergoing any visible hourglassing. Figure 5 is an example of typical hourglassing behavior when it occurred in an analysis. Analysis 5 hourglassing energies were very similar to what was plotted for analysis 4. (see appendix A, figures 8a, and 10a).

These results suggest that it is perhaps more beneficial in terms of preventing hourglassing behavior to have a dam mesh (slave) that is comparatively more fine than the foundation mesh (master) or dam and foundation meshes that are of approximately the same density. Alternately, considering master/slave relationships, it could also be said that having a master surface mesh that is comparatively less fine than, or of approximately the same density as the slave surface mesh, may be beneficial in terms of reducing or preventing hourglassing.

Contact Surface Properties, Dam, and Foundation

Analyses 2 and 6 are identical except for the contact surface tiebreak values between foundation and dam. In analysis 2, a tied surface was used, and in analysis 6, a tied surface was created by using an AUTOMATIC_SURFACE_TO_ SURFACE_ TIEBREAK, with high tiebreak values. The primary difference that can be seen during the analysis runs is the dam penetration into the foundation and rock block on analysis 6 (high tiebreak values between dam and foundation/rock block). This penetration is visible at 1,000 times magnification. There is a small amount of hourglassing visible as well in analysis 6 (see fig. 6).

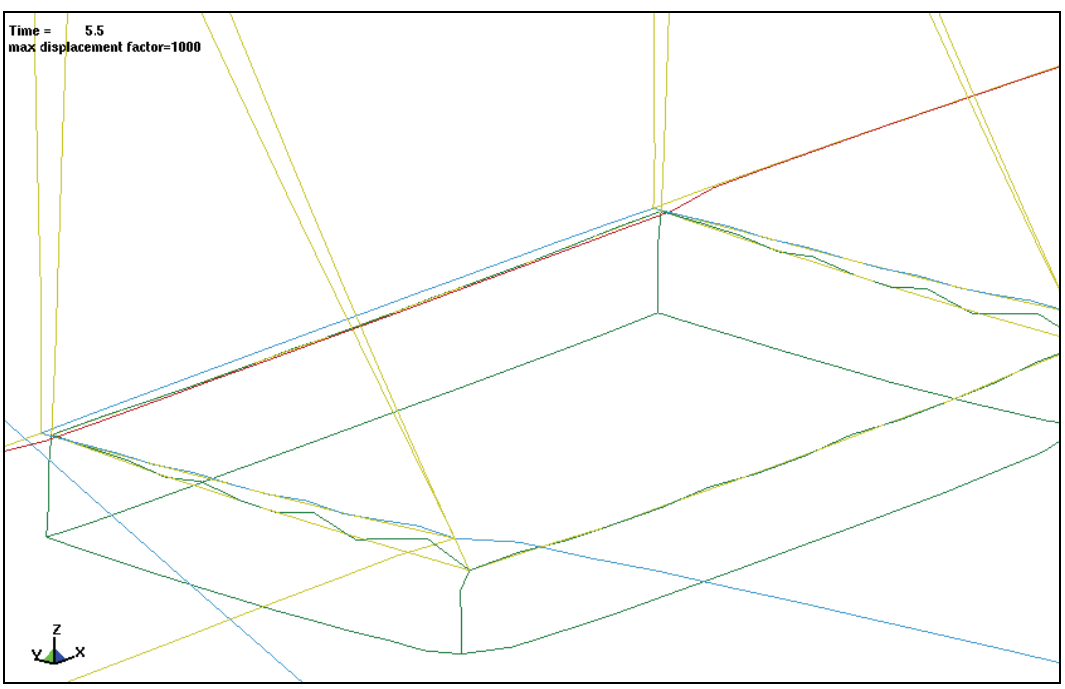


Figure 5.—Analysis 5 hourglassing behavior around rock block. IHQ (water) = 5. QM (water) = 0.10. Foundation/dam mesh = fine/fine

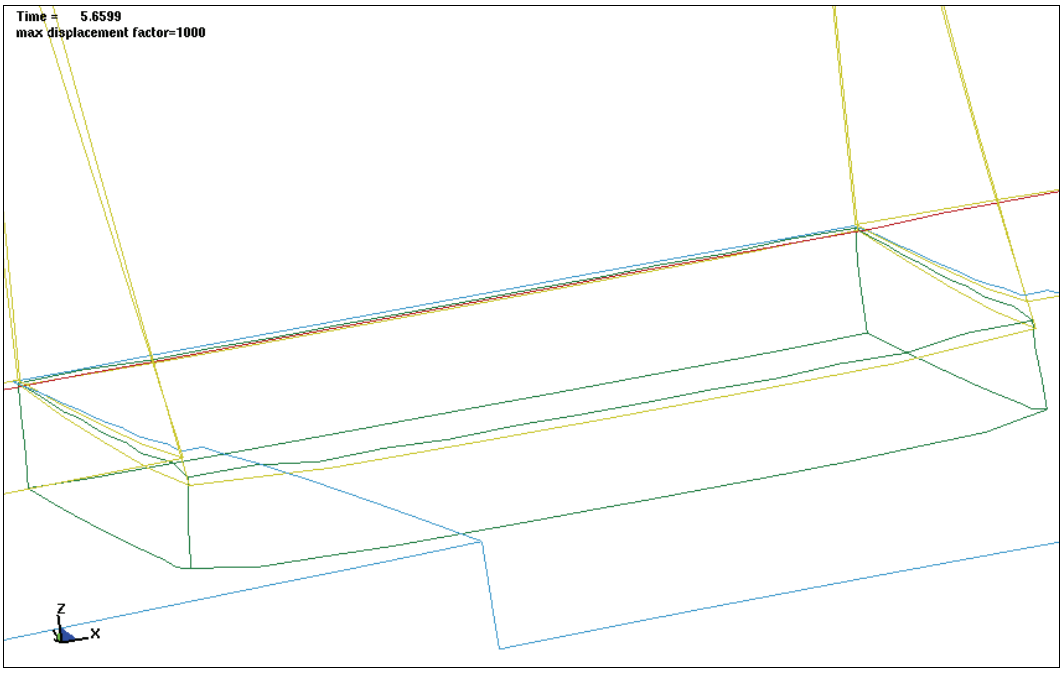


Figure 6.—Dam penetrating into foundation and rock block on analysis 6. IHQ (water) = 5. QM (water) = 0.10. Foundation/dam mesh = fine/coarse

Analyses using surface type TIED_SURFACE_TO_SURFACE did not exhibit penetration of the dam into the foundation when viewed at high magnification. Analysis 2 experiences fairly larger amounts of hourglassing in the foundation and rock block, as compared with the small amount observed in analysis 6. Foundation and rock block hourglassing energies plotted in appendix A, figures 4a and 12a are quite different between the two analyses. Foundation hourglassing energy increases by a factor of four in analysis 2, as compared to analysis 6. Rock block hourglassing energy increases by a little more than a factor of two in analysis 2, as compared to analysis 6.

These results suggest that an AUTOMATIC_SURFACE_TO_SURFACE_ TIEBREAK contact surface type with high tiebreak values may be helpful to reduce hourglassing, if the use of such a contact surface type is appropriate.

LS-DYNA Recommendation

At the recommendation of LS-DYNA, the hourglassing control type *for the fluid elements only* was changed from IHQ = 5 stiffness hourglassing control to IHQ = 1 viscous hourglassing control for the three analysis runs (4.1, 5.1, and 6.1) in which the mesh densities were varied. Hourglassing control for the dam and foundation remained at type 5 stiffness hourglassing control. Changing this value for the fluid elements, as well as changing QM to a value of 0.0001 (for the fluid elements only, also as recommended by LS-DYNA) caused the behavior of the hourglassing energy in the water to change noticeably. Using IHQ = 1 resulted in a smoother hourglassing energy curve, and a higher end value for hourglassing energy than was exhibited with IHQ = 5 in analyses 4, 5, and 6. Behavior similar to what was observed when using viscous hourglassing control globally on

analyses 1.a, 2.a, and 3.a was also seen on the plots for analysis runs 4.1, 5.1, and 6.1—the hourglassing energy increased steadily throughout the 6-second run for the materials assigned IHQ = 1, as opposed to leveling off as with stiffness hourglassing control. Although the overall hourglassing energy in the water was greater using IHQ = 1 than using IHQ = 5, the requirement that hourglassing energy be less than 10 percent of the internal energy was still satisfied for the fluid elements. (see appendix A, figures 3c, 5c, and 7c).

Another effect observed with IHQ = 1 for fluid elements was noted at 1,000 times magnification of the physical model's behavior. For IHQ = 5, the water surface remained smooth and deflected downward as it moved into the space created by the middle block of the dam moving downstream slightly under static water load. For IHQ = 1, the water surface deformed considerably more under magnification, creating an effect that almost looked like the "parting of the Red Sea." See figures 7 and 8 to see the difference in behavior for analyses 5 and 5.1.

Stiffness forms of hourglassing control are recommended for future static and seismic modeling of dam and foundation. LS-DYNA recommends the default form (IHQ = 1) for fluid elements, in conjunction with the recommended QM value for fluid elements of 0.001 to 0.0001, as discussed in the next section. However at Reclamation, stiffness forms of hourglassing control are used for fluid elements.

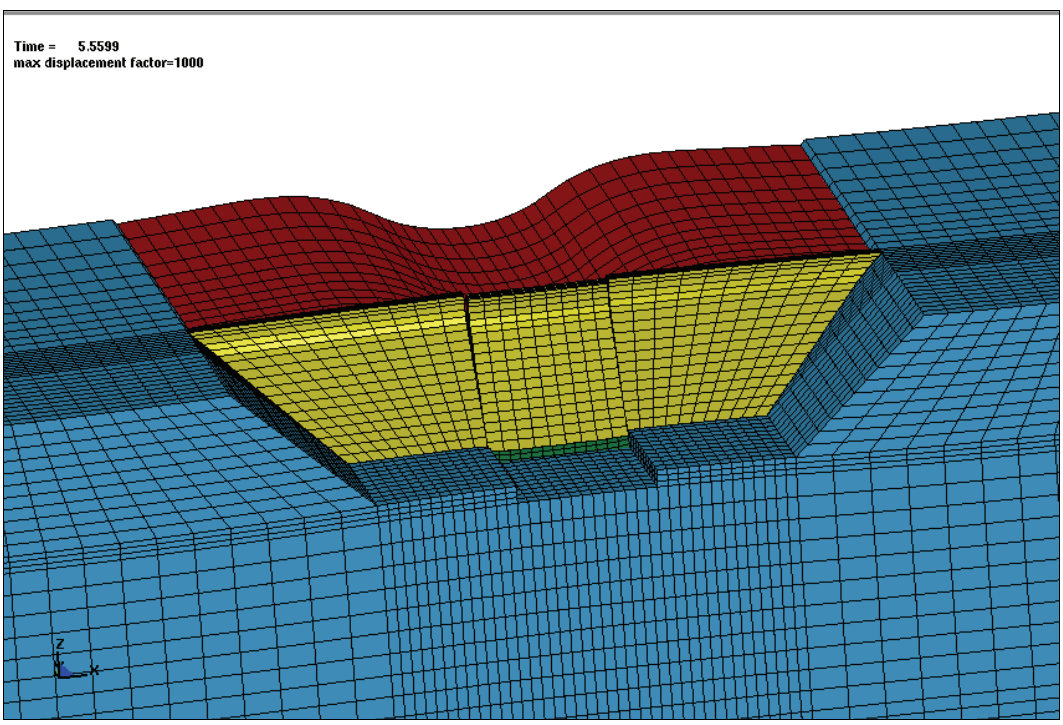


Figure 7.—Analysis 5, behavior of water at 1000x magnification. IHQ (water) = 5. QM (water) = 0.10. Foundation/dam mesh = fine/fine.

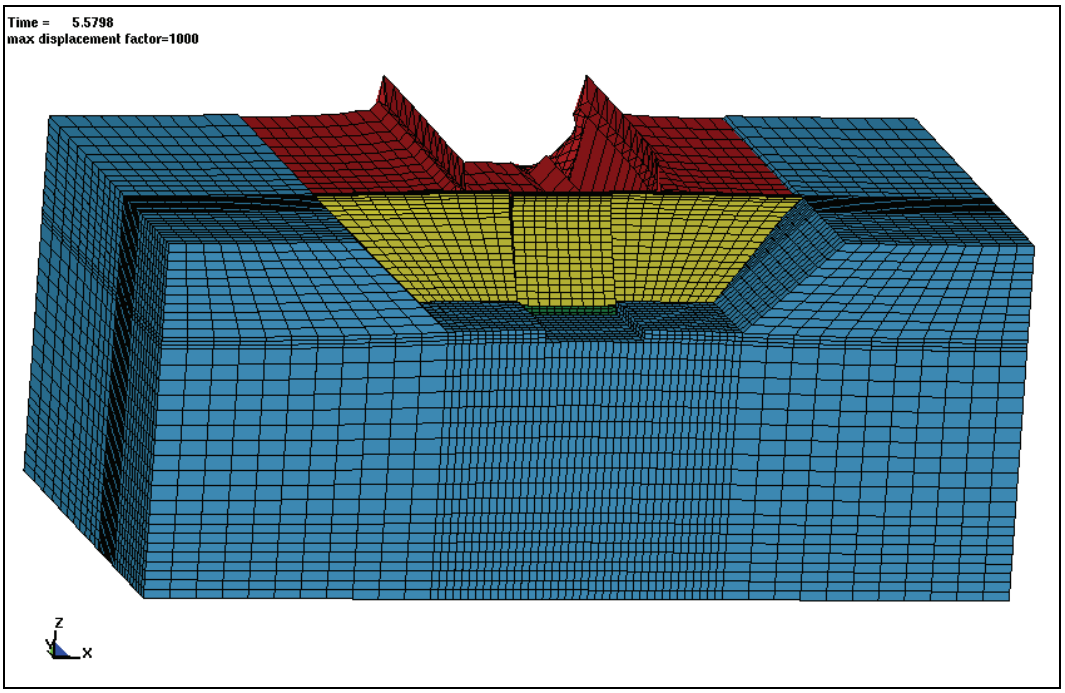


Figure 8.—Analysis 5.1, behavior of water at 1000x magnification. IHQ (water) = 1. QM (water) = 0.0001. Foundation/dam mesh = fine/fine.

Other Observations

Visual examination of the stress contour plots at the heel and toe of the dam for each of the analyses indicated that stresses were as would be expected for a dam under this loading condition (static water load over nearly the full height).

All analyses demonstrated global hourglassing energies well within the recommended 10 percent of internal energy guideline (see all "b" figures in appendix A).

Summary

To correct hourglassing problems in a model:

- For all materials except fluid elements, stiffness IHQ = 5 (*HOURGLASS [IHQ = 5]) is recommended.

- Dam (slave surface) mesh can be made comparatively finer than foundation (master surface) mesh as a means to prevent hourglassing.

- Varying QM within the range given above (0.05 – 0.15) for dam and foundation may be helpful in reducing hourglassing within a model. Smaller

values of QM should be tried first, as they have yielded slightly lower hourglassing energy results during this study.

Bulk viscosity should be allowed to function at default values. If any of the defaults need to be changed, it can be done for a single material in the *HOURGLASS card for that material, or globally in the CONTROL_ BULK_VISCOSITY card. It is not anticipated that changing the bulk viscosity defaults, or even turning off bulk viscosity altogether (by assigning very small values to the coefficients in the *CONTROL_BULK_ VISCOSITY card) will have a significant effect on the results (Livermore Software Technology Corporation, 2006).

- For fluids, use default hourglassing viscous IHQ = 1 (*HOURGLASS [IHQ = 1]). In conjunction with this, use *HOURGLASS (QM = 0.001 to 0.0001). These values should be used for fluid elements *only*. Although the behavior of the fluid elements was altered due to the use of *HOURGLASS (IHQ = 1), as discussed, it is still the recommended form of control for fluid elements. This is based on several things. First, although hourglassing energy was greater when *HOURGLASS (IHQ = 1) was used, it was still within acceptable levels (less than 10% of internal energy). Second, water pressure in the reservoir compared well to theoretical values for both *HOURGLASS (IHQ = 1) and *HOURGLASS (IHQ = 5). Because of these factors, and because LS-DYNA has recommended using *HOURGLASS (IHQ = 1) and *HOURGLASS (QM = 0.001 to 0.0001) for fluid elements, this is also the recommendation presented here.

- High normal and shear tiebreak values used with contact surface type AUTOMATIC_SURFACE_TO_SURFACE_TIEBREAK may limit hourglassing along the contact; however penetration of one surface into the other may also occur.

Use of Eulerian-Lagrangian Interaction for Seismic Loading

The Purpose of Using Arbitrary Lagrangian-Eulerian

The primary reason for attempting to use an Eulerian code in finite element analysis is to better demonstrate the behavior of a fluid material. In Eulerian codes, the model consists of a fixed mesh through which the fluid flows. Lagrangian modeling of fluid is possible. However, since fluids have little or no shear strength, significant deformation of the material in a Lagrangian analysis can reduce time steps and cause an analysis to diverge. It is also difficult to

properly model sliding interfaces between Lagrangian fluid elements and solid elements. Overly constrained nodes at intersections of multiple contact surfaces cause hourglassing and pressures in the fluid that are not accurate.

LS-DYNA offers a way to model the fluids in a Lagrangian model with an arbitrary Lagrangian-Eulerian (ALE) capability. ALE capability was developed to better model high pressure impulse type loadings in a fluid such as blasts and impacts, where large deformations of the fluid are likely. There is some concern with using ALE modeling for analyses extending to the time limits that are required for seismic analysis. ALE calculations are appropriate for a short duration problem like blast or impact. However, when ALE is used for a much longer duration analysis, the run time may be impractical. A test of the capabilities of a coupled Eulerian/Lagrangian model considering static and seismic loads is summarized here.

No Void Static Analysis

Arbitrary Lagrangian-Eulerian modeling uses a solid element mesh defined with fluid material properties and ALE material grouping to estimate the behavior of an Euler type mesh. An ALE model can consist of one or more connected parts/meshes making up the ALE domain. Multiple physical materials or multi-material-groups (MMG) may flow through this ALE domain. When the reference domain is allowed to move, it is referred to as ALE. If this domain is fixed in space, it is called Eulerian. The material is allowed to flow between the initially defined shape of the fluid body and whatever fluid area is defined around the initially water-filled area. Figure 9 shows the simple model that will be used to illustrate implementing ALE in a model. This model consists of a wide canyon and dam made up of three blocks. All three dam blocks are tied to the foundation. Figure 10 shows an example of the mesh region used to define the ALE portion of the analysis. Figure 11 shows the initial remeshing of the ALE mesh region.

One of the major benefits that LS-DYNA offers in modeling water using ALE is that all of the interfacing between ALE cells and Lagrangian elements is done internally by the code. The user is not required to specify these interfaces as would be required in a purely Lagrangian analysis.

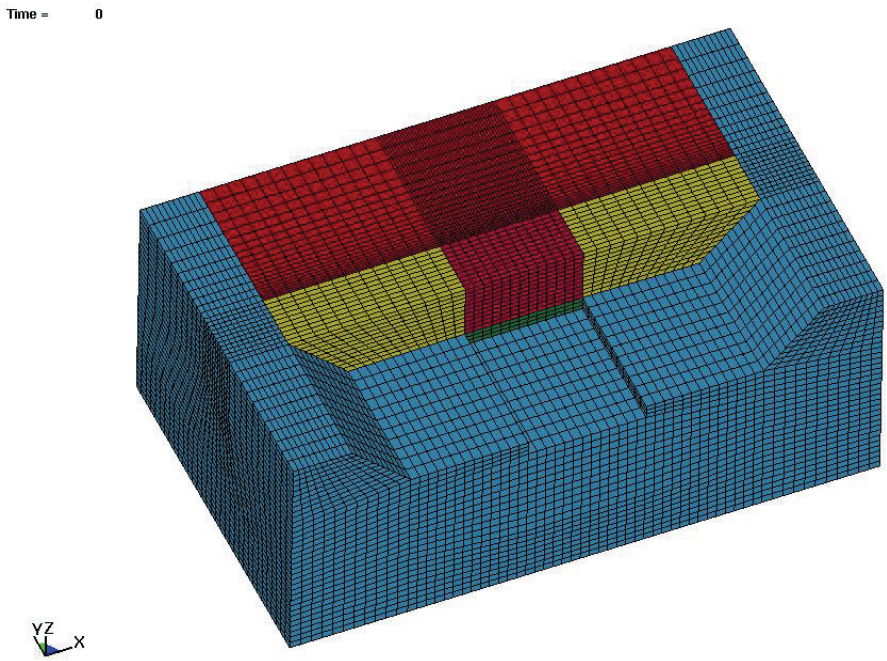


Figure 9.—Simple Model Used for Illustrating the Implementation of ALE.

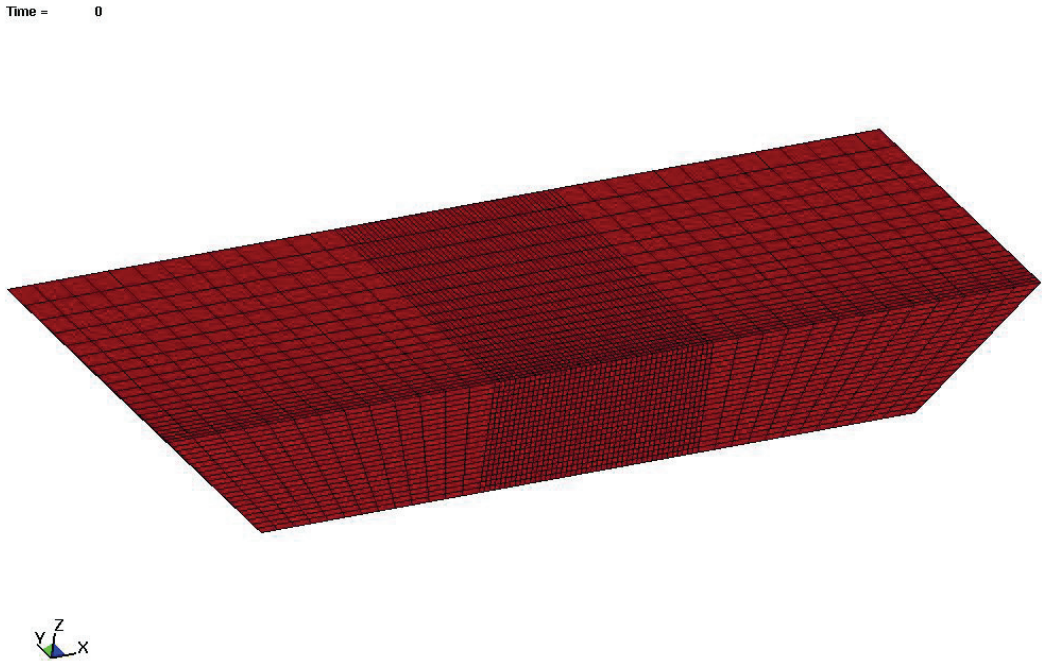


Figure 10.—Fluid Defined Using Hexahedron Elements.

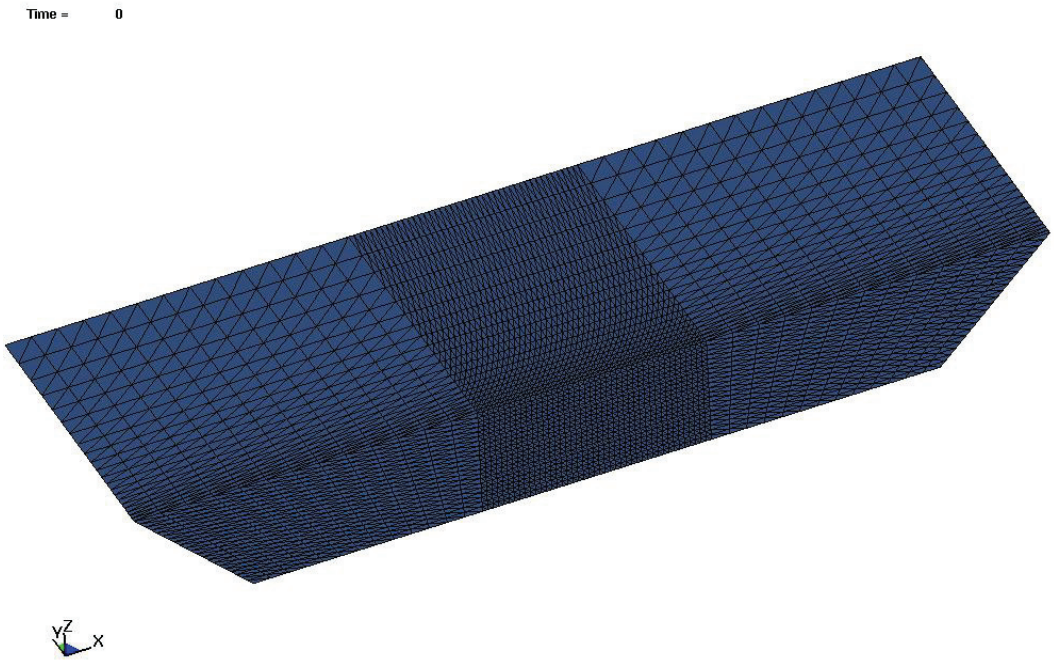


Figure 11.—Initial R-meshing of the ALE Mesh Region Shown in figure 10.

To set up an ALE coupled problem, the cards that need to be used are as follows. Refer to the LS-DYNA manual (Livermore Software Technology Corporation, 2006) for information for each individual problem.

Group parts into group entities:

```
*set_part_list
card 1
card 2
*set_part
card 1
card 2
```

Indicate that ALE analysis will be used:

```
*CONTROL_ALE
card 1
card 2
```

Define which part groups will be used for ALE type elements in the analysis:

```
*ALE_MULTI-MATERIAL_GROUP
card 1
card 2
```

Enable and define coupling between the slave Lagrange elements and the master ALE cells (ALE is always the master):

```
*CONSTRAINED_LAGRANGE_IN_SOLID
card 1
card 2
card 3
```

Define the water material:

```
*MAT_NULL
1,0.0000933,0.0,0.0,0.0,0.0,0.0,0.0
*HOURGLASS
1,1,1e-6
*EOS_LINEAR_POLYNOMIAL
1,0.0,316100.0,0.0,0.0,0.0,0.0,0.0
0.0,0.0
*SECTION_SOLID
1,11,0
*PART
materialtype#9(Fluid)
1,1,1,1,1,0,0,0
```

In the example described here, the initial model was used to test the application of gravity loads to the system. There was no void space in this model. The water was modeled using ALE elements, and the foundation and dam were modeled using Lagrangian elements.

A benefit to using ALE is that loads can be applied very quickly. In a Lagrangian system, gravity is usually ramped on over a number of seconds to ensure stability of the water elements. Gravity was applied to this model over a span of only 0.1 second of computational time. The pressures are accurate. This is shown in figure 12.

This model behaved very well under static loads. The correct water pressures were calculated.

Void Static Analysis with Sliding

Next an analysis was run with the same configuration, only this time a void space was defined downstream of the water where the middle dam block was located. When the dam block was released and allowed to slide, the water should have flowed into the void space to fill the gap that was left from the block moving.

Figure 13 shows the added block of void into which the water could flow when the dam block slid.

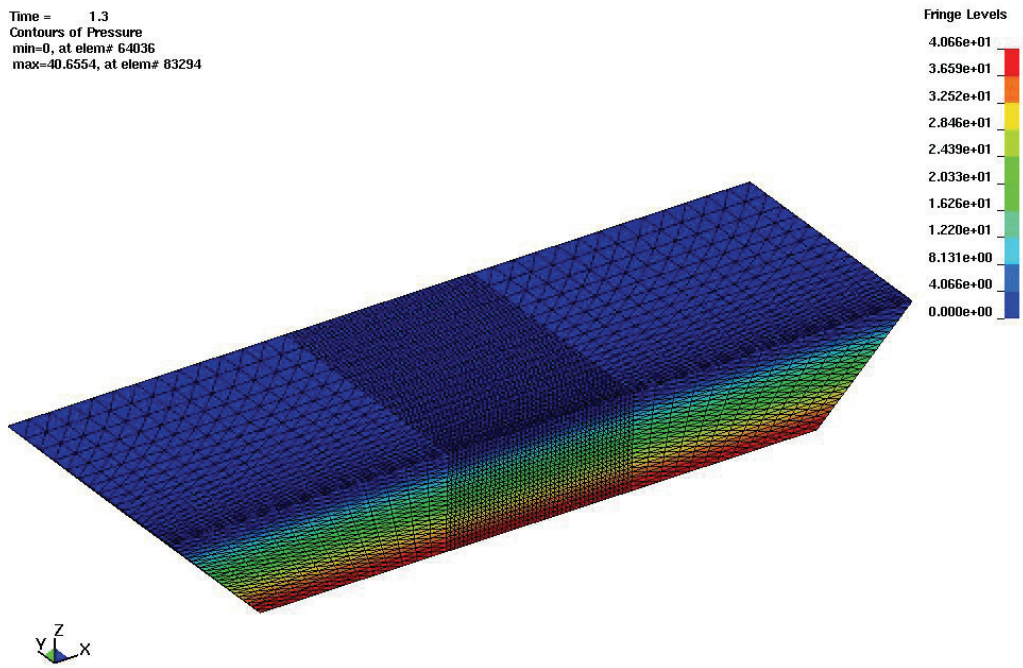


Figure 12.—Water pressures in ALE elements.

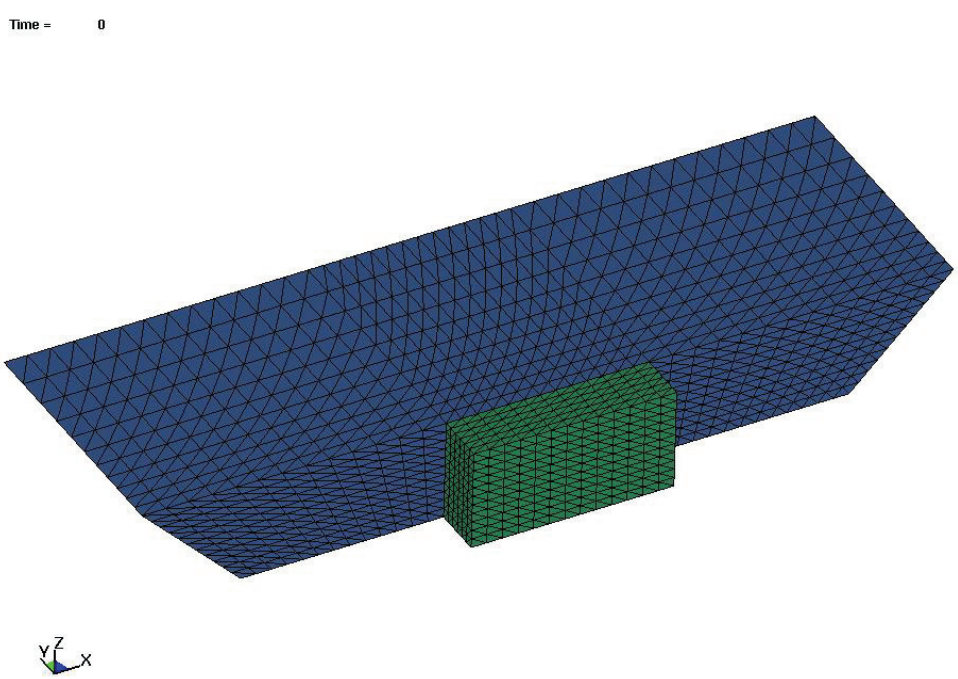


Figure 13.—Modified water mesh to include void space.

The following code was added to define the ALE void portion of the input file.

Define the empty (void) area into which the fluid may flow:

```
*mat_vacuum
5
*HOURGLASS
5,1,1e-6
*SECTION_SOLID
5,11,0
*PART
materialtype#9(Fluid)
5,5,5,,5,0,0,0
```

A plot of pressures in the water after the block began to slide is shown in figure 14.

As shown above, the water pressures were not correct after the dam began to slide. The uniform water pressure profile was lost when sliding occurred, and incorrect pressures were calculated in the water.

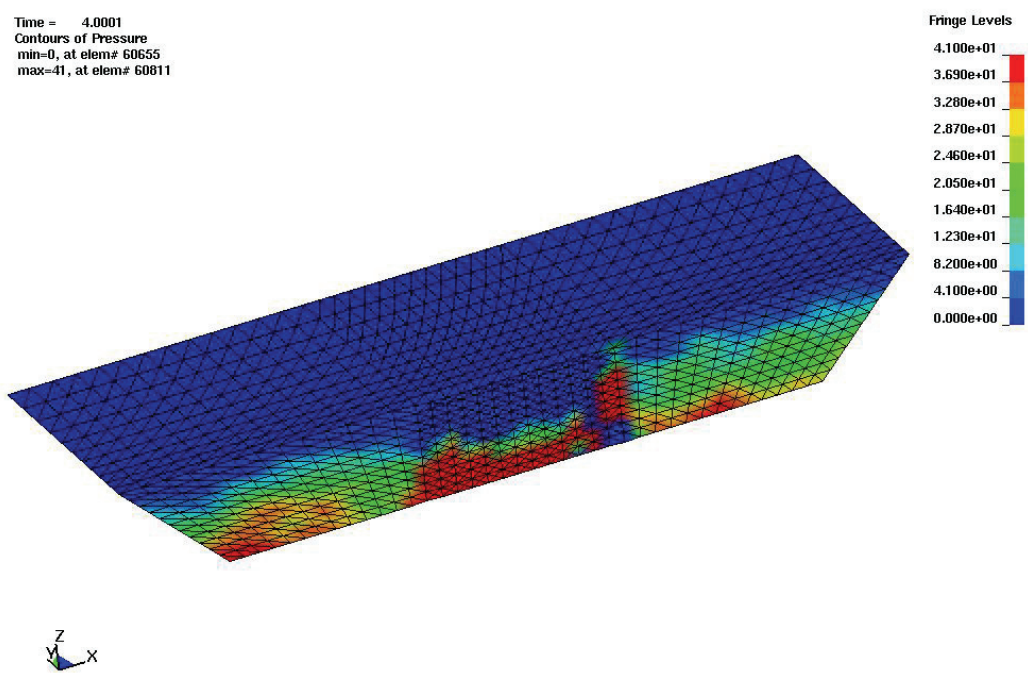


Figure 14.—Water Pressures after Sliding of the Dam Block.

Earthquake Analysis with Tied Dam Blocks

Next, an analysis was run with the dam tied to the foundation so sliding was not allowed. An earthquake load was applied to a horizontal plane of nodes deep in the foundation, and the water pressures on the dam were measured. The results of this analysis were compared to the results from an analysis of the same model using Lagrangian elements for the water. The measurements for the water pressures are shown in figures 15 and 16.

In the ALE analysis, the water does not respond correctly with a seismic load applied. The dynamic changes in pressure seen in the Lagrangian elements was not captured with an Eulerian water mesh.

These analyses show that when water was modeled using an Eulerian mesh, a large wave hit the dam one time at approximately 13 seconds, and no other significant interaction occurred between the water and the dam during the seismic event.

Conclusions

It does not appear that ALE can be used for seismic analyses at this time.

If the structure is sliding, ALE will not give dependable results for even a static analysis.

The significant errors in pressures stem from the magnitude of pressures being calculated. ALE was developed for blast and impact type loadings, in which pressures much greater than atmospheric pressures are experienced. Pressures experienced during seismic loads are comparable to atmospheric pressures. Small errors in the calculation of atmospheric pressure are not noticeable when comparing them to 50 atmospheres or more experienced during a blast load. ALE was not designed to work with a seismic pressure range of 1 to 2 atmospheres.

Another significant problem with using ALE for seismic loading involves durations greater than milliseconds. Again, errors in the calculation with relation to displacement of the fluid and filling of the void areas are not noticed over a millisecond time span. However, over a time span of 60 seconds, these errors add up and make a significant impact on the pressures and final shape of the displaced fluid.

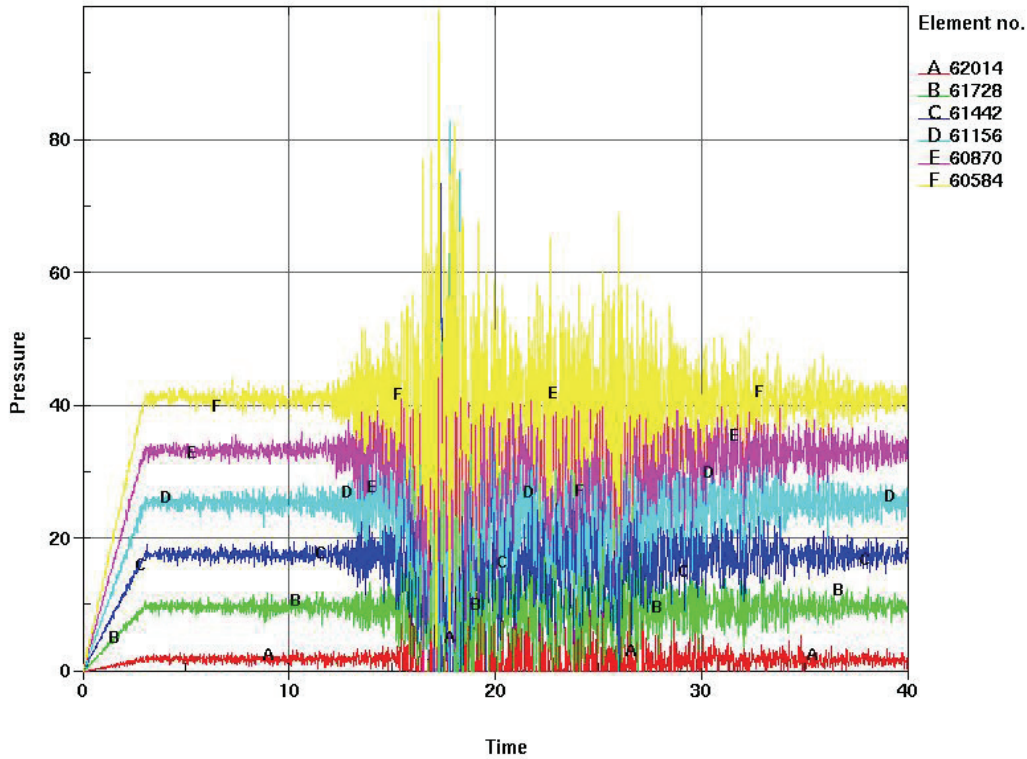


Figure 15.—Water pressures on dam during earthquake application calculated using LaGrangian elements.

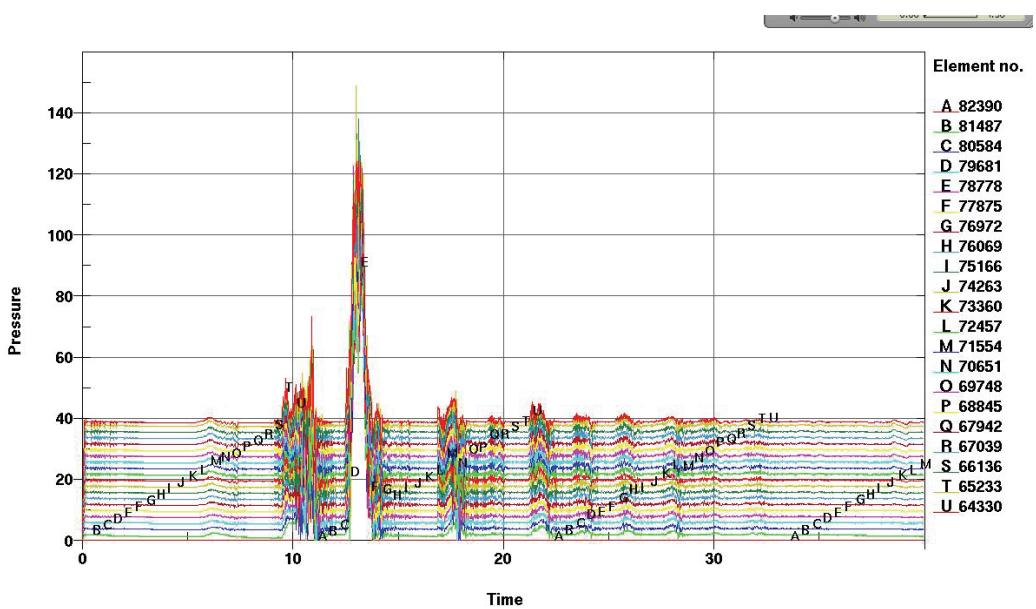


Figure 16.—Water pressures on dam during earthquake application calculated using ALE water.

Application of Traction Loads

Background

At Reclamation, seismic time history loads have traditionally been applied using accelerations or velocities at depth in the foundation. These loads were applied on a horizontal plane of nodes within the foundation. They could not be applied on a face that also had a boundary condition that allows dissipation of energy (nonreflecting boundaries). Application of accelerations or velocities at a plane in the foundation results in a "fixed" or rigid plane at which the seismic input originates. Complications in the propagation of vertical waves occur because the vertical waves are reflected back up at the plane of application resulting in trapped energy. This is seen as a spike in the vertical component of the acceleration response spectra at the fundamental vertical mode of the foundation.

When loads are applied as *traction loads*, the wave is not trapped by the plane of application, and energy can be removed at the infinite boundary at the base of the model in addition to the vertical sides of the model.

Traction Loads—Details

The application of traction forces is accomplished by inputting pressure and traction loads along a plane of element faces at depth in the foundation. The magnitude of the pressure is a function of the velocity and the material properties of the foundation, including the shear wave velocity and the pressure wave velocity. At each element face, there is a vertical component $F(t)_v$, which is a pressure load applied perpendicularly to the element face.

$$F(t)_z = \left[\frac{2E'A_i}{C_p}\right] v_z(t)$$

where,

$$E' = \frac{E(1-\nu)}{(1+\nu)(1-2\nu)}$$

There are also two horizontal components that apply loads parallel to the surface of the element:

$$F(t)_x = \left[\frac{2GA_i}{C_s}\right] v_x(t) \qquad F(t)_y = \left[\frac{2GA_i}{C_s}\right] v_y(t)$$

where,

$F(t)_x$, $F(t)_y$, $F(t)_z$ = time history force (lb)
E' = a variation of the elastic modulus (lb/in^2)
G = shear modulus (lb/in^2)
A = contributing horizontal area around node (in^2)
C_s = S-wave velocity (in/s)
C_p = P-wave velocity (in/s)
$v_x(t)$, $v_y(t)$ = deconvolved horizontal ground velocity (in/s)
$v_z(t)$ = deconvolved vertical ground velocity (in/s)

When traction loads are applied on a plane that also has a nonreflecting boundary, the force time histories must be modified to account for dampers at the input location. For vertical motions, the following force must be added to $F(t)_y$:

$$F'(t)_z = v_z(t) \times A_i \times \rho \times \sqrt{\frac{K + \frac{4}{3}G}{\rho}}$$

For horizontal motions, the following must be added to F_x and F_z:

$$F'(t)_x = v_x(t) \times A_i \times \rho \times \sqrt{\frac{G}{4 \times \rho}}$$

$$F'(t)_y = v_y(t) \times A_i \times \rho \times \sqrt{\frac{G}{4 \times \rho}}$$

where,

K = bulk modulus
ρ = mass density

Finite Element Model

The model for this study was a parallelepiped with dimension that are typical of a foundation model used in Reclamation analyses: horizontal dimension, 5,475 by 5,465 feet, and vertical dimension, 2,950 feet (fig. 17). The load was applied along a plane located 925 feet above the base.

The problem was first analyzed using velocity time histories at nodes as input. The analysis was repeated using traction forces at element faces as input, and the results were compared. The response of a node at the center of the top surface was considered. No damping was applied in these analyses.

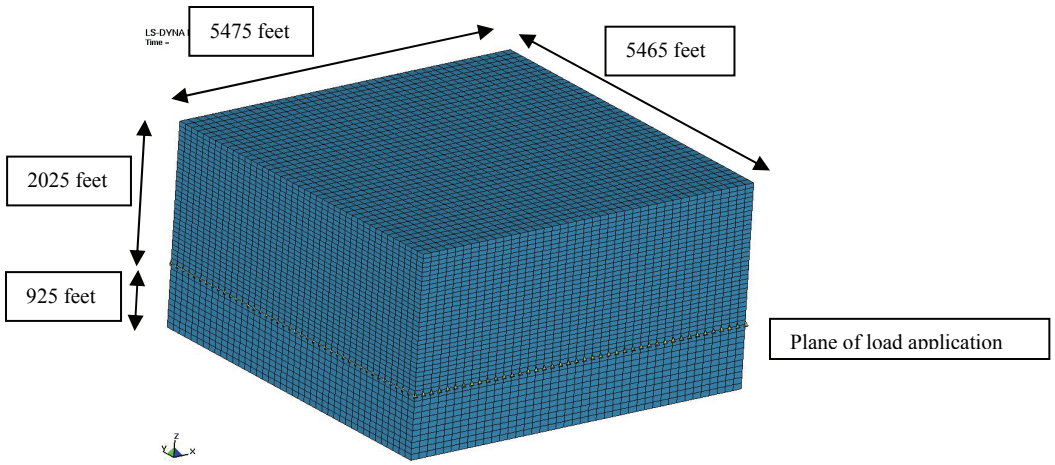


Figure 17.—Finite element model.

LS-DYNA

The command to apply traction loads in LSDYNA is *LOAD_SEGMENT_SET_ NONUNIFORM. The information applied by the user includes a load curve, a set of element faces along the plane of load application, a scale factor, and the direction cosines

A faceset is defined in TrueGrid at the plane of load application. The *LOAD_ SEGMENT_ SET_NONUNIFORM command allows pressures loads to be applied in each of the three global directions. The user then inputs the appropriate scale factor in each direction, $F'_x(t)$, $F'_y(t)$, and $F'_z(t)$, as defined above. The pressures loads are converted internally to forces at nodes based on the area of the element face, resulting in forces being applied in the foundation in all three directions.

Gravity Load Application

An initial stress state was calculated prior to application of the seismic time history (transient) loads. This was accomplished by applying fixities perpendicular to the foundation vertical faces and the base face during the application of gravity loads. The gravity loads were applied over several seconds followed by several seconds of quiet time. For both dynamic analyses, the fixities were replaced with nonreflecting boundaries, and the forces generated during the static analysis are ramped during the application of the vertical body force. The model was allowed to come to equilibrium at the appropriate initial state of stress prior to the application of the dynamic loads.

In the case of applied traction loads, the vertical forces along the base need to be checked for accuracy. If this is not done, due to round-off error, the loads

generated by the fixities may not be equal to the force of the mass of the model as it is accelerated upward, resulting in drift of the entire model. The vertical forces can be modified by a scale factor to correct this discrepancy. It should be noted here that this is not necessary in the dynamic analysis in which nodal velocities (or displacements or accelerations) are applied because the load application itself dictates the movement of the entire model. The nodes of the plane of application are forced to move in a certain manner.

Results

The results are presented for the analysis with seismic loads input as both time history velocities and time history traction loads. The following output is presented for a node at the center of the top surface:

- Displacement, velocity, and acceleration results
- Fast Fourier transform (FFT) information for the velocity time histories
- Response spectra

Displacement, Velocity, and Acceleration Results

In table 5, the maximum and minimum displacements, velocities, and accelerations are compared for each loading type. Also included in this table are the maximum and minimum velocities for the target motions.

While the maximum and minimum displacements in the velocity run, the traction load run, and the target motion are comparable, this is not true for the velocities and accelerations. Maximum velocities and accelerations from the velocity run can be as high as 3.5 times the target value. In the traction load run, these values never exceed 1.5 times the target value.

It is apparent from the analysis results that the velocity output from the analysis using traction loads is in closer agreement with the target values than the velocity output from the analysis using nodal velocities as input. While the values in the tables are an indication of the differences, the time history plots of the velocities and accelerations show marked differences (app. B).

A comparison of the target time history motions with the results of these two analyses shows that the displacements, velocities, and acceleration from the traction load analysis are in agreement, while the velocity and acceleration records from the velocity analysis are dissimilar.

FFT Results

The velocity and acceleration plots from the analysis with nodal velocities as input contain high frequency components. When seismic loads are input as velocities (or displacements or accelerations) on the plane of application, that plane of nodes is essentially fixed by the applied loads. The shear waves and compressive waves cannot penetrate the plane of application and be refracted out

of the model at the base by the nonreflecting boundary. Figures in appendix B contain the FFT plots for the velocity records from both analyses. It can be seen that for the horizontal motions, the output from the analysis with velocity as input contains frequencies equal to approximately 5.5, 8.2, 10.5, 12.7, and 15.0 Hz. These frequencies are not found in any measurable amount in the analysis using traction loads as input. In the vertical direction, the predominant frequency in the analysis with velocities as input is approximately 2.0 Hz. The same record from the traction load analysis shows a broader range of frequencies. See table 6 for data on these frequencies.

Response Spectra Results

The final comparison makes use of the acceleration spectral intensity (ASI), which is defined as the area under the acceleration response spectrum between 2 and 10 Hz and is an indication of energy that would affect structures of interest for Reclamation. Table 7 contains this parameter for both the velocity and the traction analysis for all three directions and for the target motion. It can be seen that the ASI for the vertical component of the velocity run is almost 3 times the ASI for the target motion. In the case of the traction loads, the ASI is only 1.2 times the ASI for the target motion.

Summary

The application of traction loads as seismic input more closely matches the target surface motions. A comparison of maximum and minimum values of velocity and acceleration as well as frequency content leads to this conclusion. The comparison of ASI values indicates that any structure modeled on the surface of the foundation would be subject to excess energy during a seismic analysis.

Table 5.—Displacement, acceleration, and velocity minimum and maximum comparisons

	Velocity loads	Traction loads	Target motions
X displacements	-0.5, 0.82	-0.5, 0.6	n/a
Y displacements	-2.2, 1.4	-1.8, 1.1	n/a
Z displacements	-4.8, -2.1	-4.5, -2.4	n/a
X velocity	-8.5, 8.0	-7.0, 7.8	-7.8, 7.2
Y velocity	-16, 17	-15, 12	-15.9, 10.8
Z velocity	-14, 16	-6.5, 8.5	-5.3, 4.4
X acceleration	-266, 259	-158, 166	-123, 162
Y acceleration	-788, 869	-305, 290	-230, 259
Z acceleration	-278, 274	-104, 139	-116, 89

Table 6.—FFT X, Y, and Z direction frequencies

X direction frequencies			
Velocity loads		Traction loads	
Frequency	Amplitude	Frequency	Amplitude
0.486	2.46	0.486	101.20
		0.886	77.91
1.181	1.98	1.147	96.32
1.546	3.33	1.563	159.70
1.98	5.69	1.98	395.90
2.293	4.97	2.276	443.70
2.484	3.32	2.484	368.60
3.544	2.29	3.405	130.30
		4.691	33.24
5.525	2.85	5.368	38.31
		6.654	39.90
		7.227	30.29
		7.609	18.79
8.183	3.96	8.53	12.73
10.493	2.43		
12.717	2.64		
15.01	9.49		
Y direction frequencies			
Velocity loads		Traction loads	
Frequency	Amplitude	Frequency	Amplitude
0.469	6.49	0.486	346.50
1.355	5.35	1.442	312.50
1.998	5.24	1.998	523.70
		2.397	404.40
		2.745	238.00
		3.075	244.20
3.822	2.76	3.544	111.40
		4.361	43.04
		4.916	41.14

5.49	1.94	5.368	48.75
		5.785	43.91
		6.671	35.88
		7.661	43.95
8.183	17.10		
		9.955	33.52
10.511	25.12		
12.752	14.99		
15.01	5.45		
Z direction frequencies			
Velocity loads		Traction loads	
Frequency	Amplitude	Frequency	Amplitude
		0.469	182.20
		1.077	178.30
1.442	4.67	1.442	310.80
1.98	24.94	1.98	300.20
2.484	12.23	2.484	371.10
		4.916	45.94
5.455	3.00	5.803	51.03
8.165	1.11		
9.573	1.13		
9.816	1.20		
10.493	0.79		
12.734	0.35		
14.976	0.43		

Table 7.—Acceleration spectral intensity (cm/s)

	Velocity loads	Traction loads	Target motions
X component	378.8	372.9	338.9
Y component	700.7	549.1	498.8
Z component	658.6	284.1	229.8

References

Flanagan, D.P., T. Belytschko, "A uniform strain hexahedron and quadrilateral with orthogonal hourglass control," *Int. J. Numer. Methods Eng.*, 17, 1981, 679-706.

Bureau of Reclamation, *State-of-Practice for the Nonlinear Aalysis of Concrete Dams at the Bureau of Reclamation*, January 2006.

Livermore Software Technology Corporation, *LS-DYNA: Keyword User's Manual*, Version 970, April 2003.

Livermore Software Technology Corporation, *LS-DYNA Theory Manual*, 2006.

Appendix A—Effect of Hourglassing—Figures

Additional figures

Figure 1.a – Mesh densities, analyses 1, 1.a, 2, 2.a, 3, 3.a, 6 and 6.1

Figure 1.b – Mesh densities, analyses 4 and 4.1

Figure 1.c – Mesh densities, analyses 5 and 5.1

The following set of figures is given for each of the twelve analyses:

Figure .a – Hourglass energy per material

Figure .b – Global internal and hourglass energies

Figure .c – Water, internal and hourglass energies

Figure .d – Foundation, internal and hourglass energies

Figure .e – Rock block, internal and hourglass energies

Figure .f – Dam, internal and hourglass energies

Figure .g – Max shear stress at right foundation contact near rock block (not given for Analyses 4.1, 5.1 and 6.1)

Figure .h – Max principal stress at right foundation contact near rock block (not given for Analyses 4.1, 5.1 and 6.1)

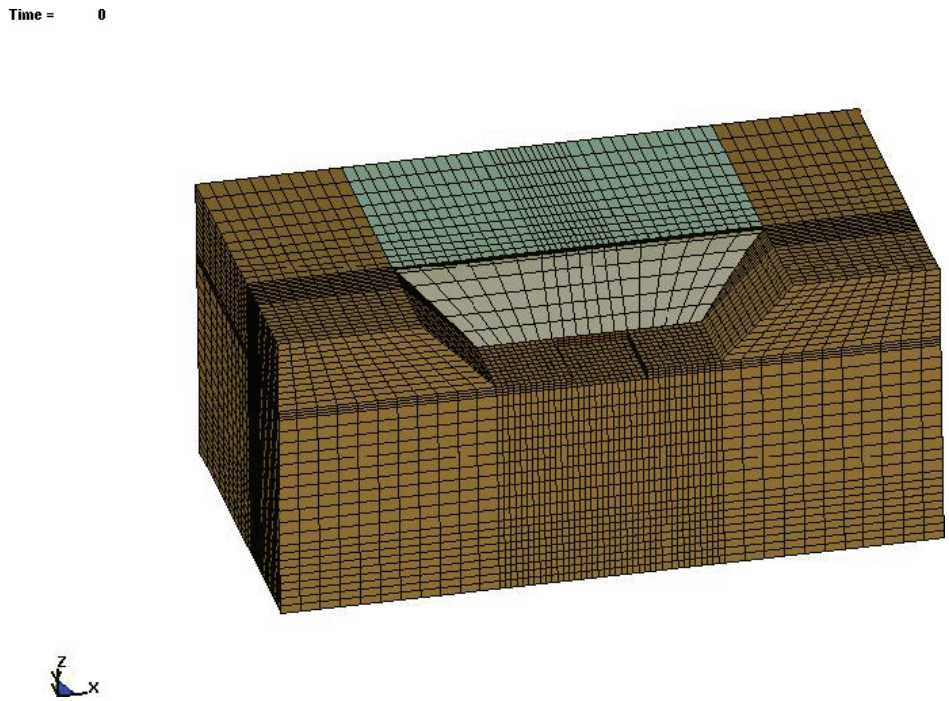


Figure 1a –Mesh densities, Analyses 1, 1.a, 2, 2.a, 3, 3a, 6 & 6.1

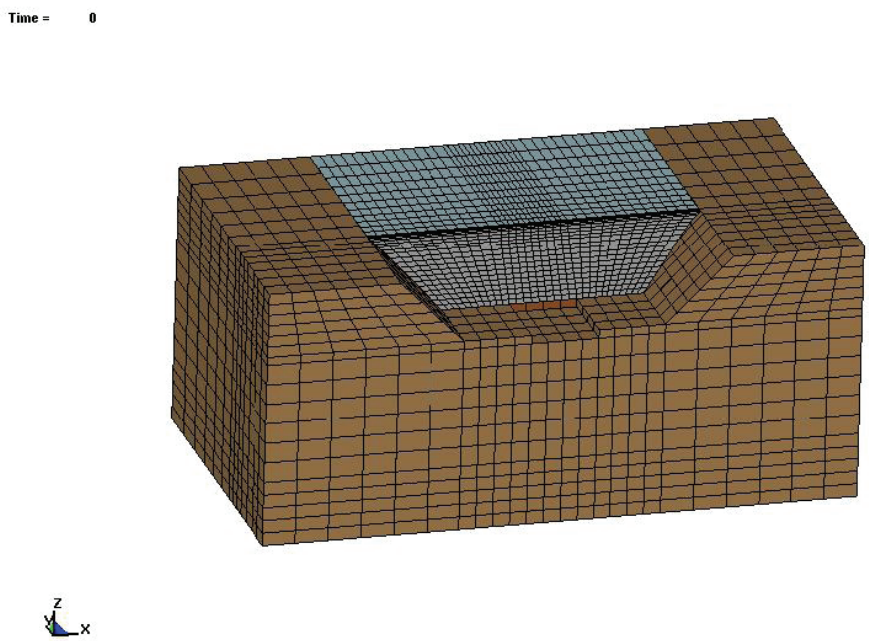


Figure 1b –Mesh densities, Analyses 4 & 4.1

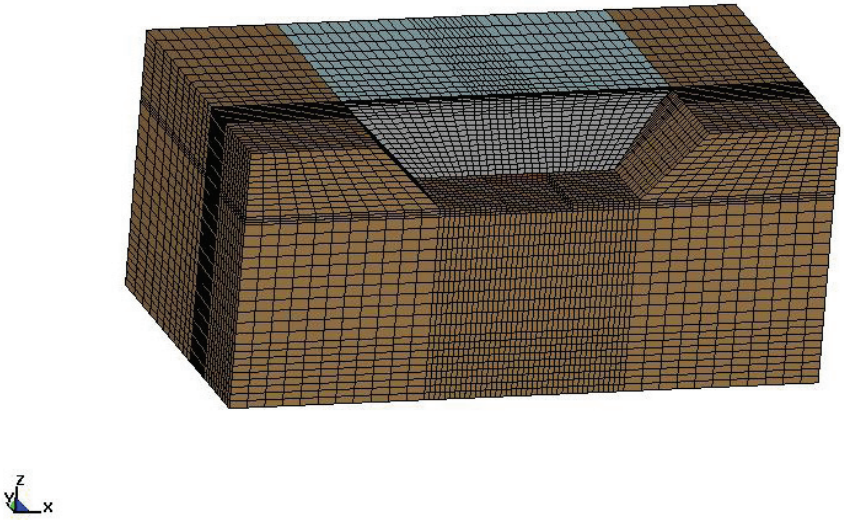


Figure 1c –Mesh densities, Analyses 5 & 5.1

ANALYSIS 1
Analysis characteristics

IHQ (dam)	5
IHQ (foundation and rock block)	5
IHQ (water)	5
QM (dam)	0.05
QM (foundation and rock block)	0.05
QM (water)	0.05
Foundation/dam mesh sizes	fine/coarse
Water/foundation contact	SURFACE_TO_SURFACE
…..notes	
Dam/water contact	SURFACE_TO_SURFACE
…..notes	
Foundation/dam contact	TIED_SURFACE_TO_SURFACE
…..notes	static and dynamic friction = 0.57
Rock block/foundation contact	AUTOMATIC_SURFACE_TO_SURFACE_TIEBREAK
…..notes	
Contraction joints	AUTOMATIC_SURFACE_TO_SURFACE_TIEBREAK
…..notes	static and dynamic friction = 0.57

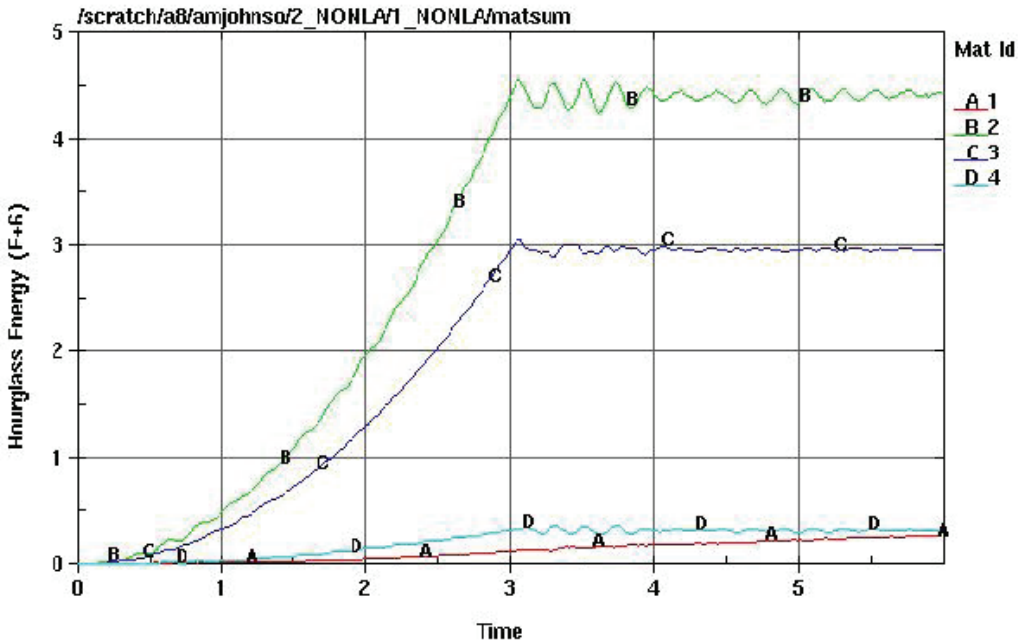


Figure 2a –Analysis 1 hourglass energy per material

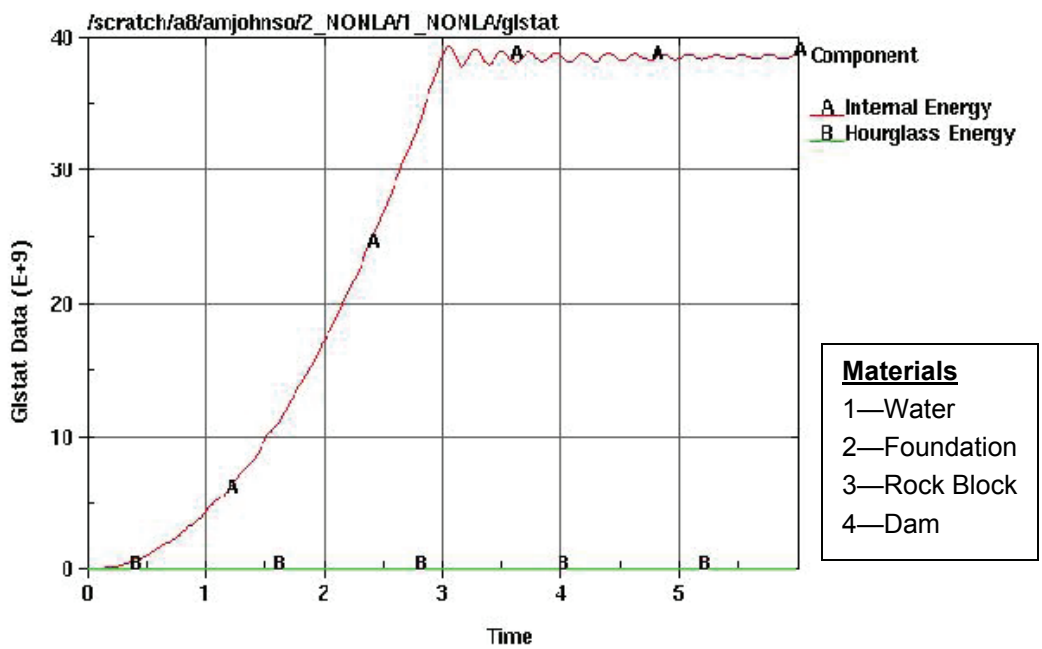


Figure 2b –Analysis 1 global internal and hourglass energies

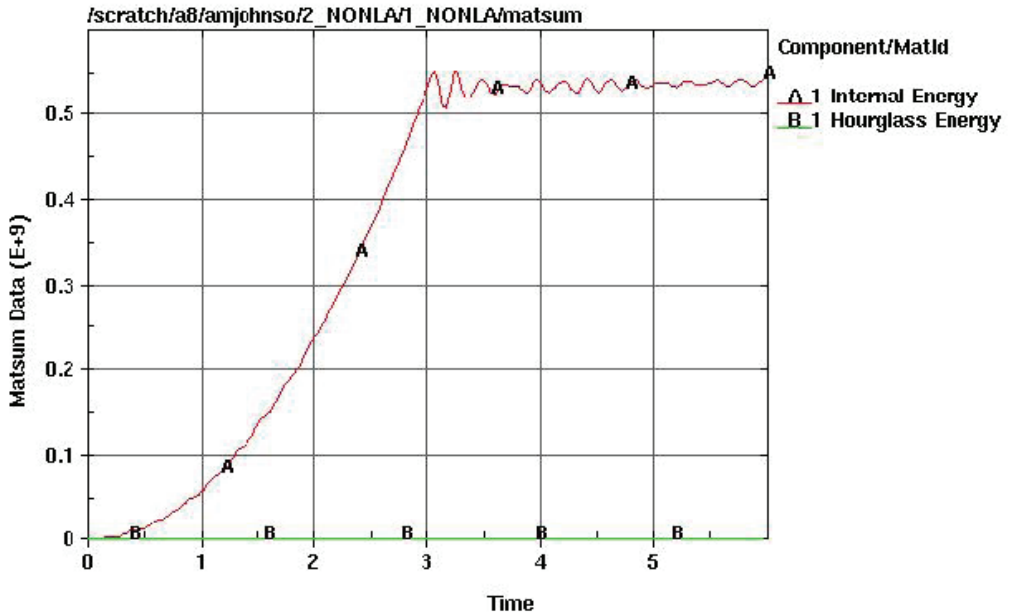


Figure 2c –Analysis 1, water, internal and hourglass energies

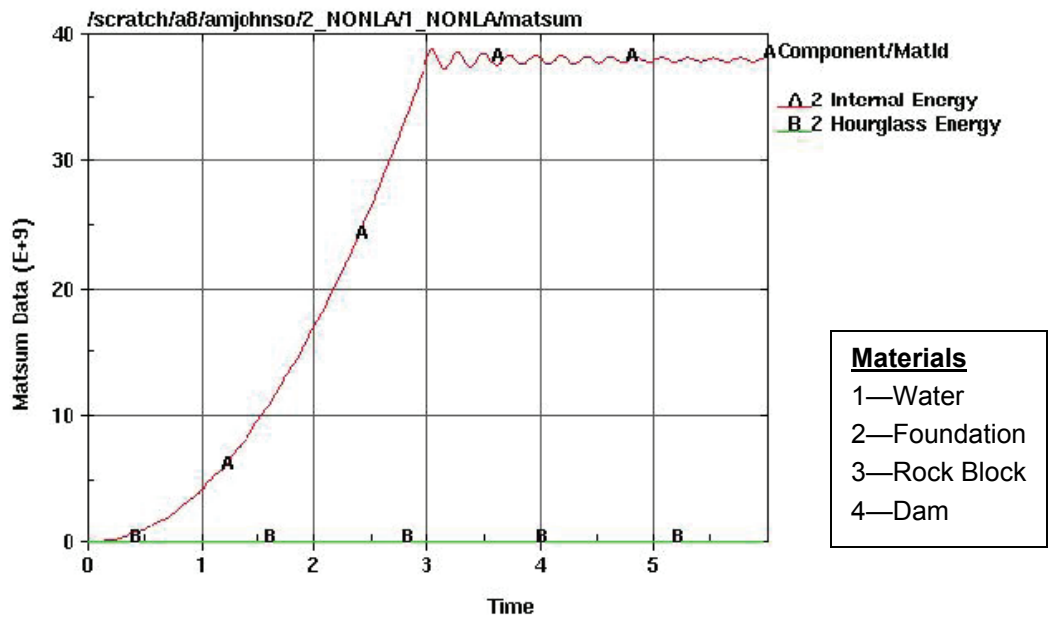


Figure 2d –Analysis 1, foundation, internal and hourglass energies

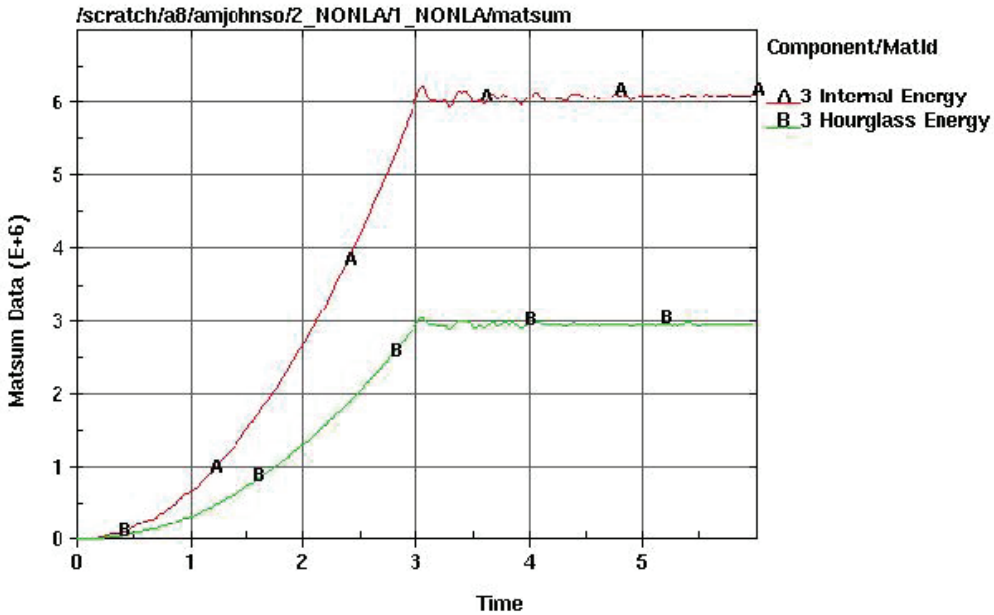


Figure 2e –Analysis 1, rock block internal and hourglass energies

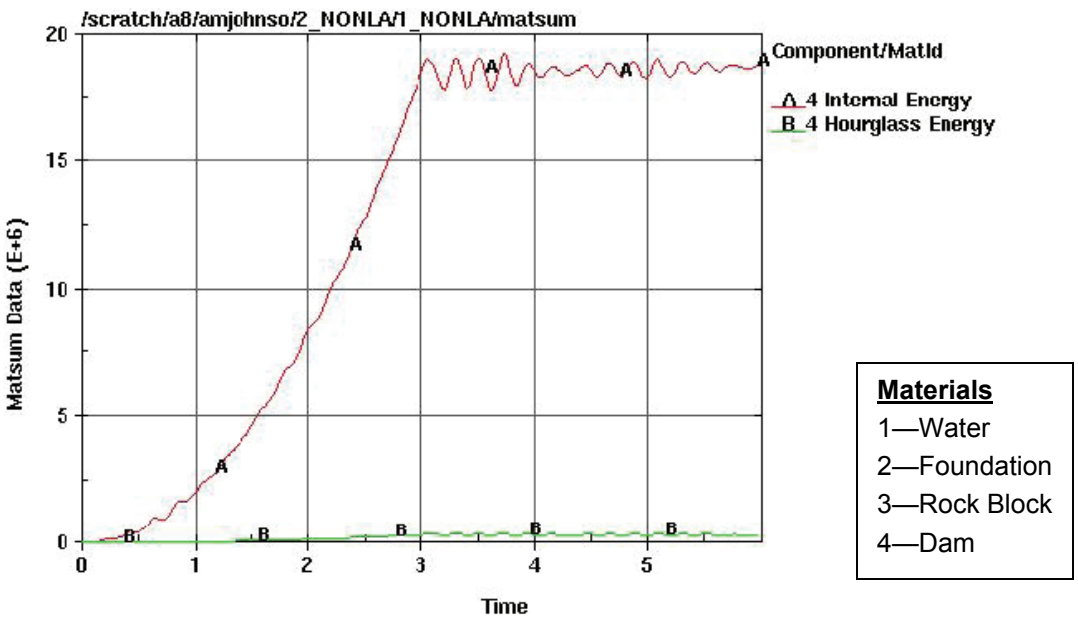


Figure 2f –Analysis 1, dam internal and hourglass energies

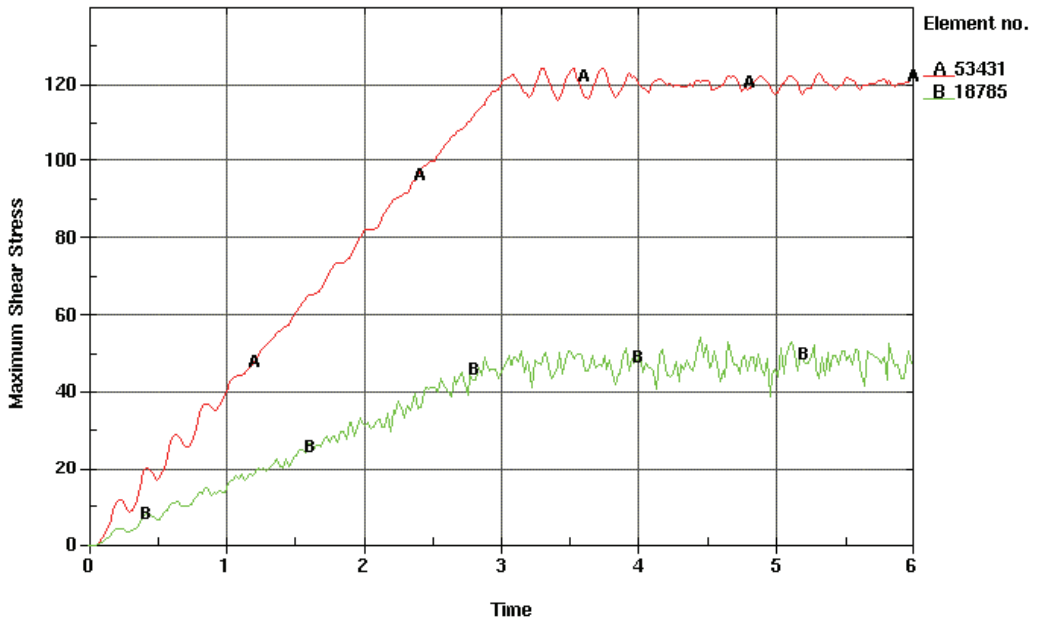


Figure 2g –Analysis 1, max shear stress at right foundation contact near rock block.

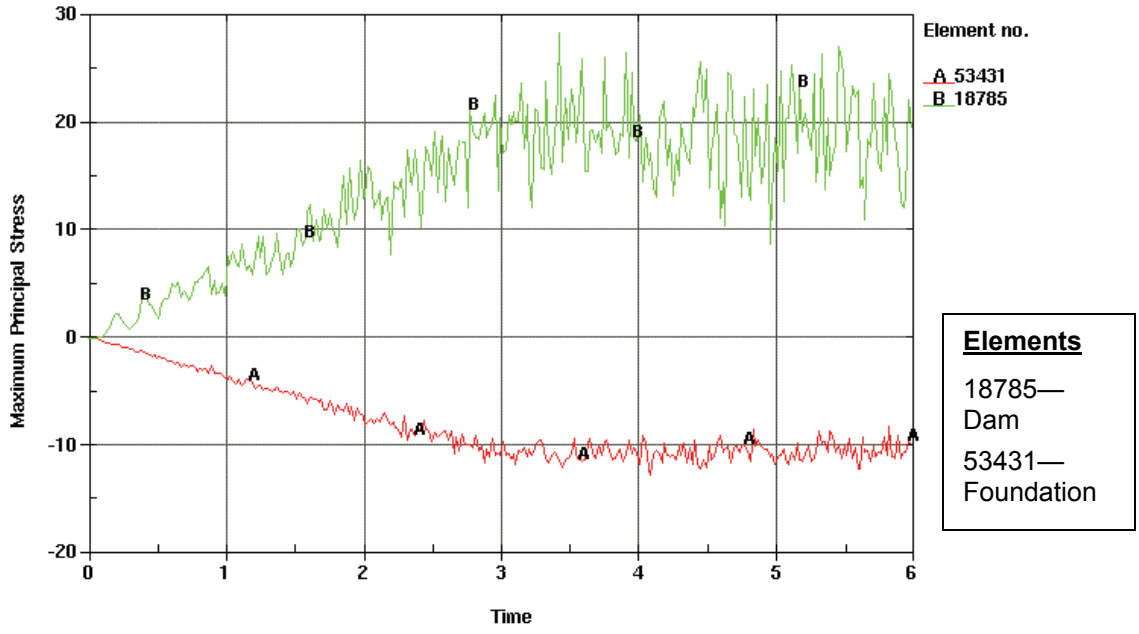


Figure 2h –Analysis 1, max principal stress at right foundation contact near rock block.

ANALYSIS 1a
Analysis characteristics

IHQ (dam)	3
IHQ (foundation and rock block)	3
IHQ (water)	3
QM (dam)	0.05
QM (foundation and rock block)	0.05
QM (water)	0.05
Foundation/dam mesh sizes	fine/coarse
Water/foundation contact	SURFACE_TO_SURFACE
…..notes	
Dam/water contact	SURFACE_TO_SURFACE
…..notes	
Foundation/dam contact	TIED_SURFACE_TO_SURFACE
…..notes	static and dynamic friction = 0.57
Rock block/foundation contact	AUTOMATIC_SURFACE_TO_SURFACE_TIEBREAK
…..notes	
Contraction joints	AUTOMATIC_SURFACE_TO_SURFACE_TIEBREAK
…..notes	static and dynamic friction = 0.57

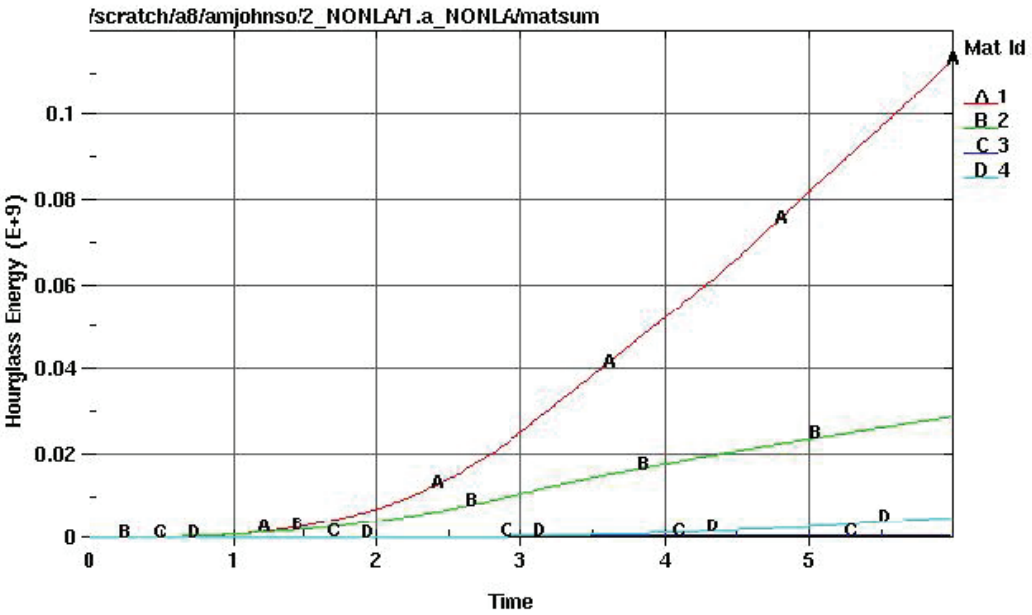


Figure 3a –Analysis 1.a hourglass energy per material

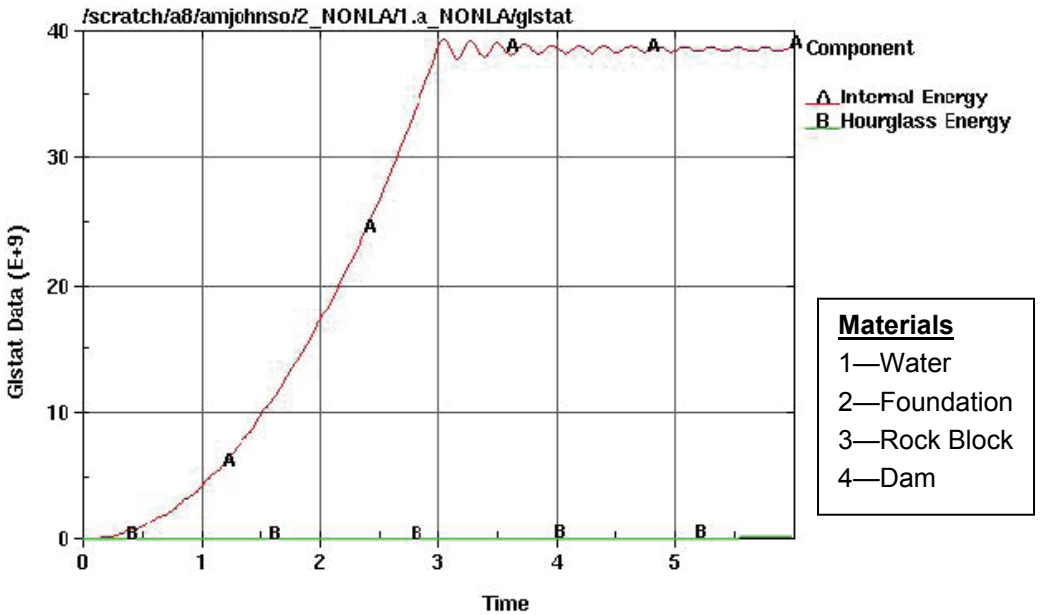


Figure 3b –Analysis 1.a global internal and hourglass energies

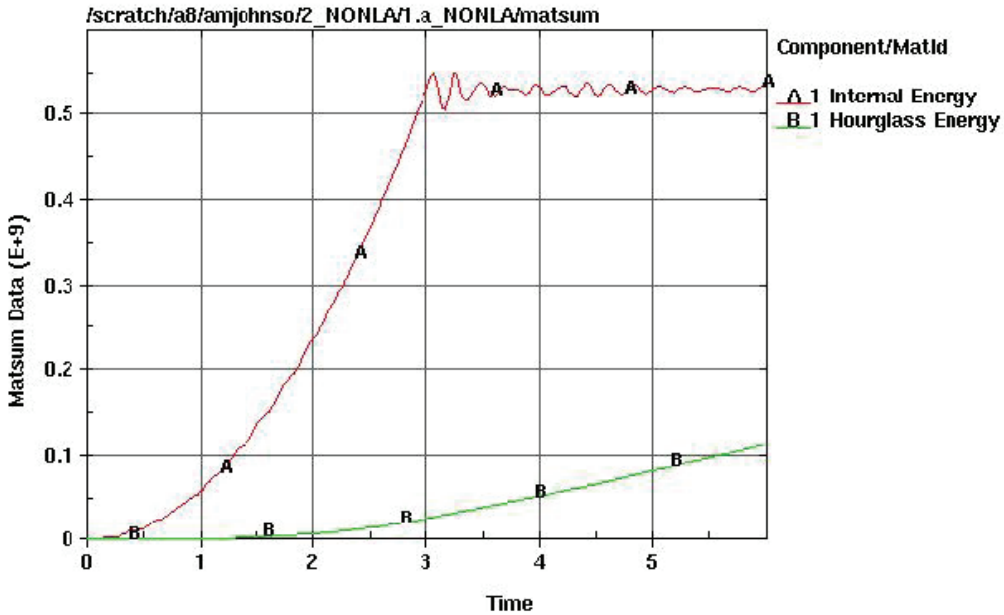


Figure 3c –Analysis 1.a, water, internal and hourglass energies

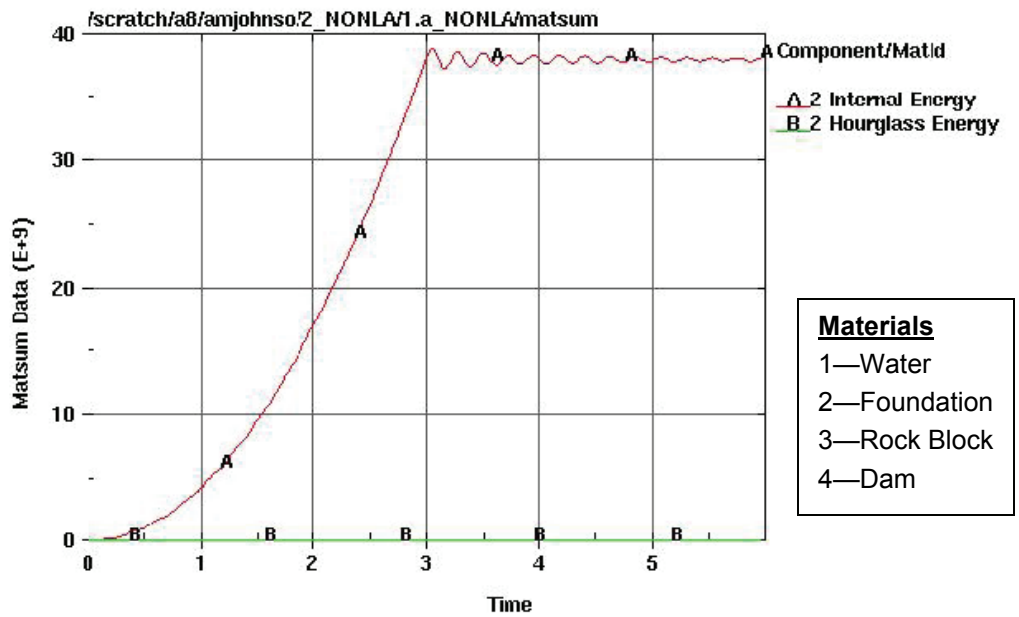


Figure 3d –Analysis 1.a, foundation, internal and hourglass energies

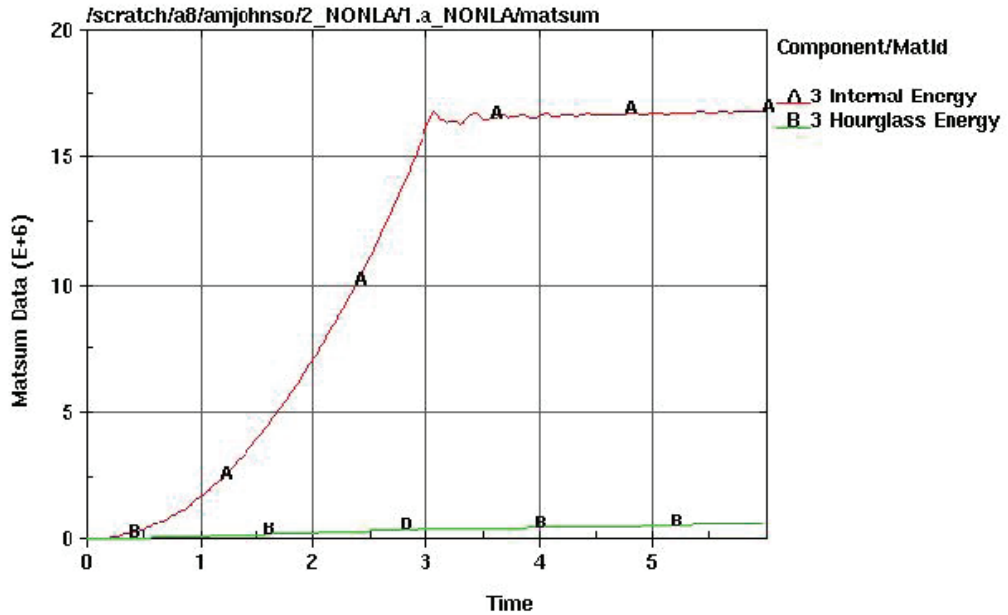


Figure 3e –Analysis 1.a, rock block internal and hourglass energies

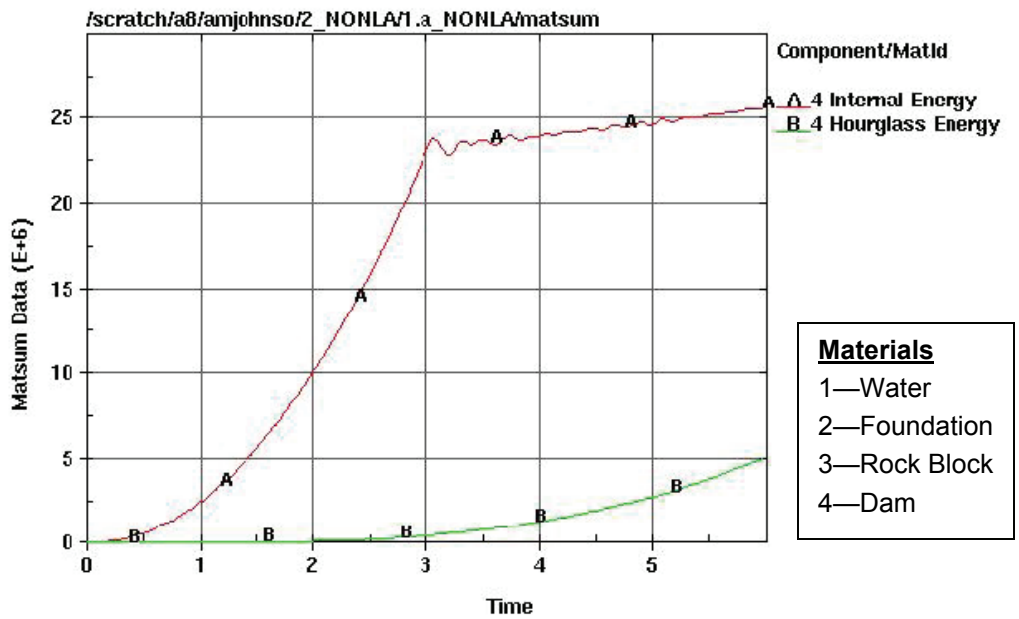


Figure 3f –Analysis 1.a, dam internal and hourglass energies

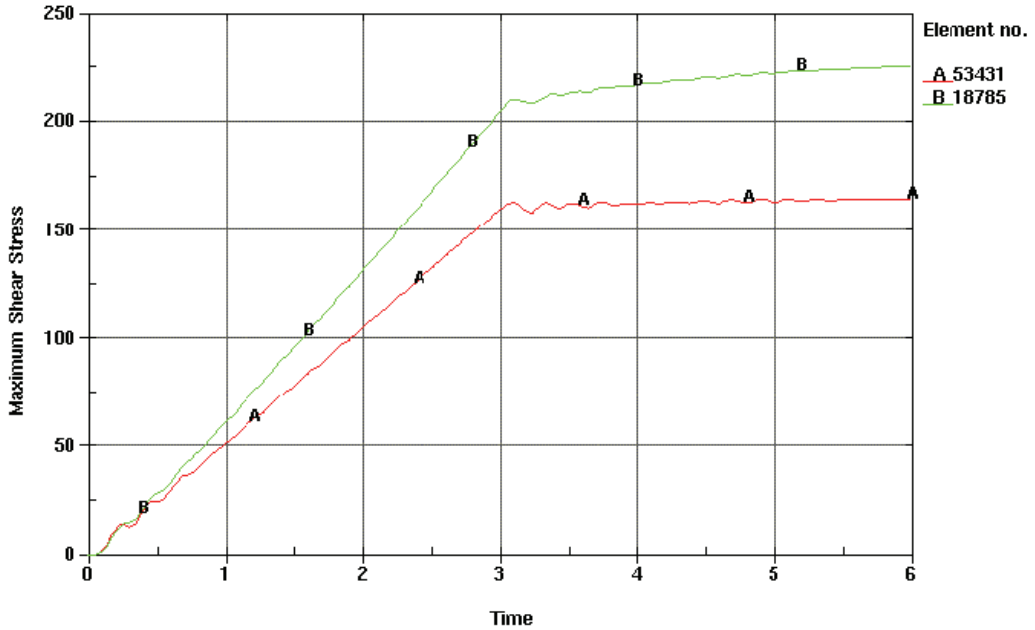


Figure 3g –Analysis 1.a, max shear stress at right foundation contact near rock block.

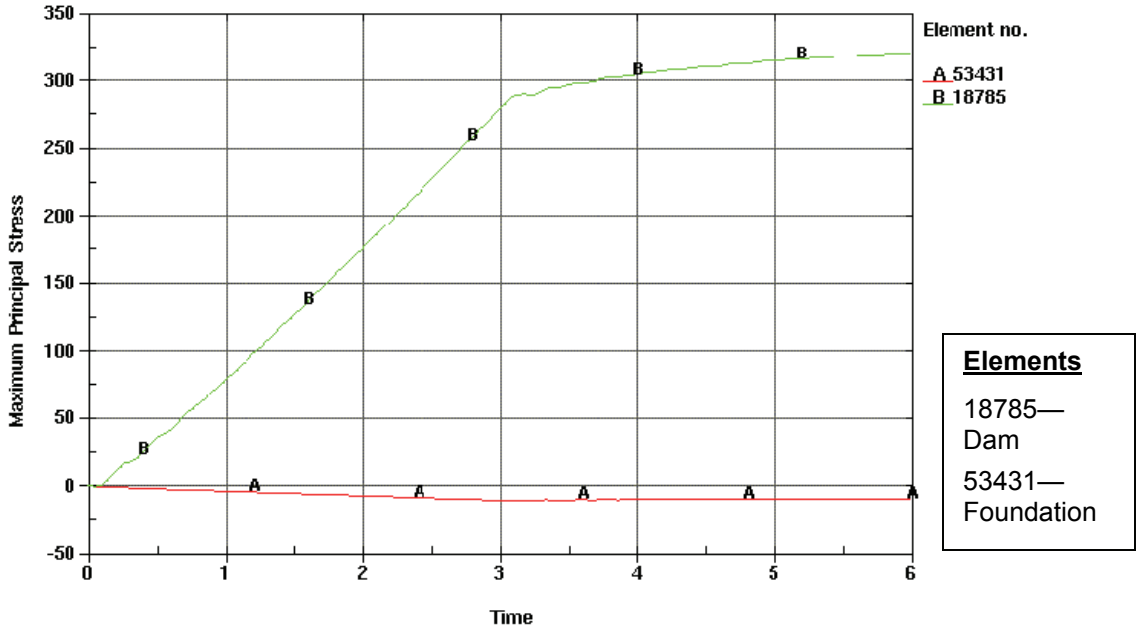


Figure 3h –Analysis 1.a, max principal stress at right foundation contact near rock block.

ANALYSIS 2
Analysis characteristics

IHQ (dam)	5
IHQ (foundation and rock block)	5
IHQ (water)	5
QM (dam)	0.10
QM (foundation and rock block)	0.10
QM (water)	0.10
Foundation/dam mesh sizes	fine/coarse
Water/foundation contact	SURFACE_TO_SURFACE
…..notes	
Dam/water contact	SURFACE_TO_SURFACE
…..notes	
Foundation/dam contact	TIED_SURFACE_TO_SURFACE
…..notes	static and dynamic friction = 0.57
Rock block/foundation contact	AUTOMATIC_SURFACE_TO_SURFACE_TIEBREAK
…..notes	
Contraction joints	AUTOMATIC_SURFACE_TO_SURFACE_TIEBREAK
…..notes	static and dynamic friction = 0.57

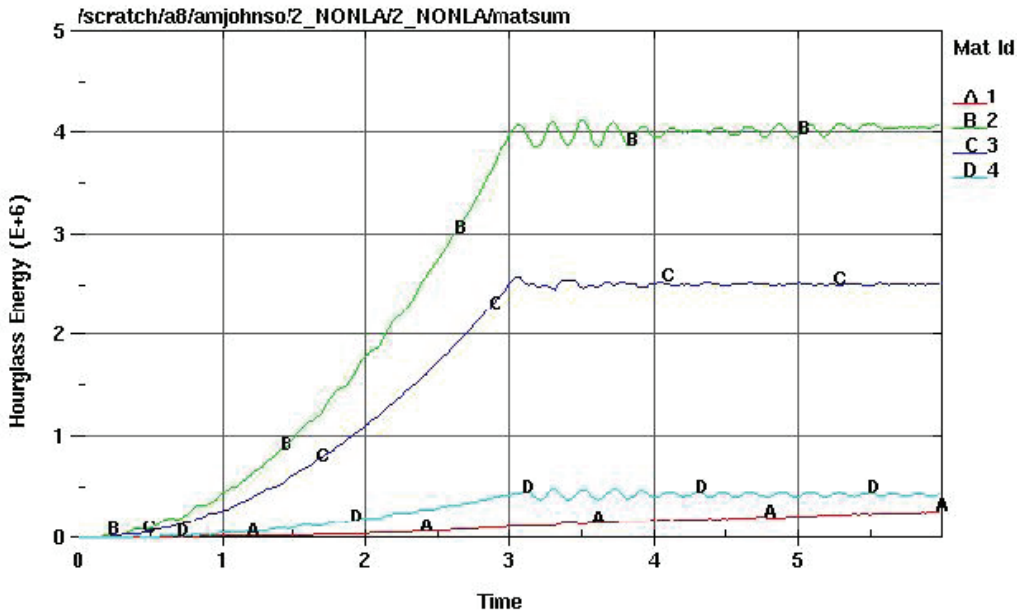


Figure 4a –Analysis 2 hourglass energy per material

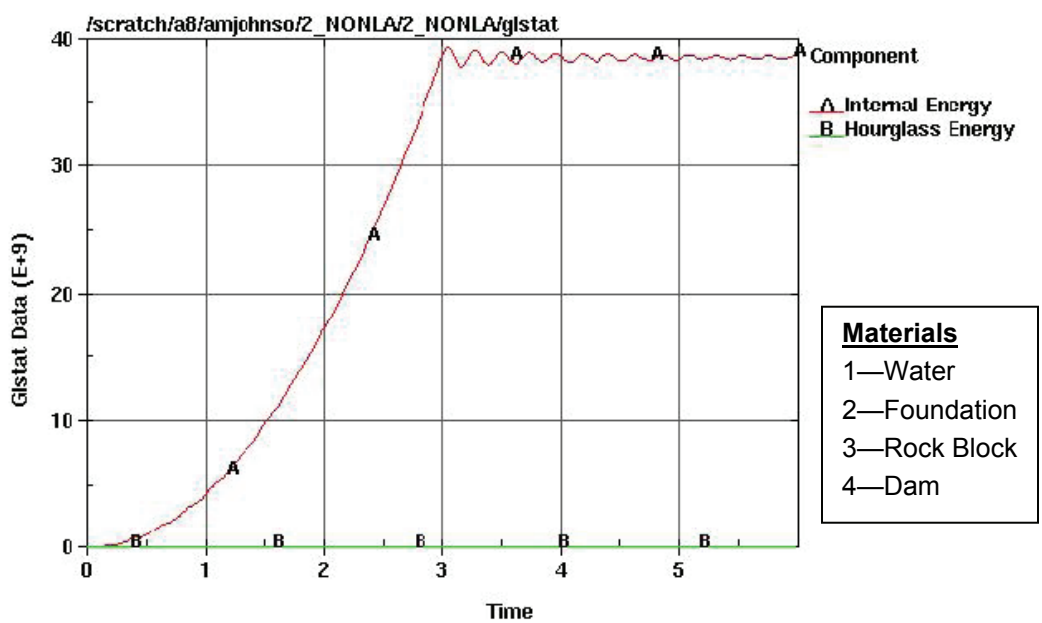


Figure 4b –Analysis 2 global internal and hourglass energies

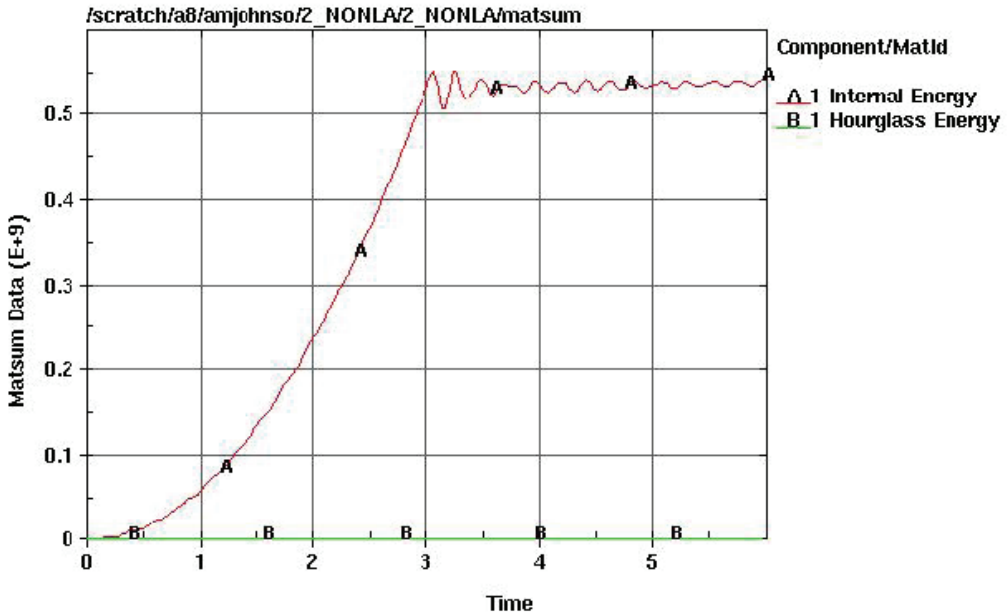


Figure 4c –Analysis 2, water, internal and hourglass energies

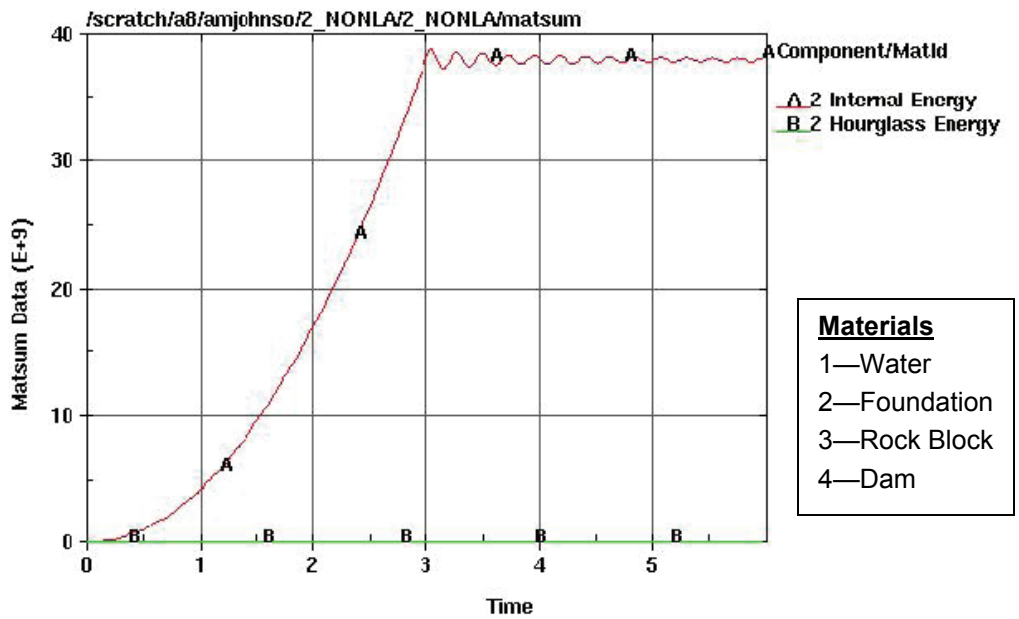


Figure 4d –Analysis 2, foundation, internal and hourglass energies

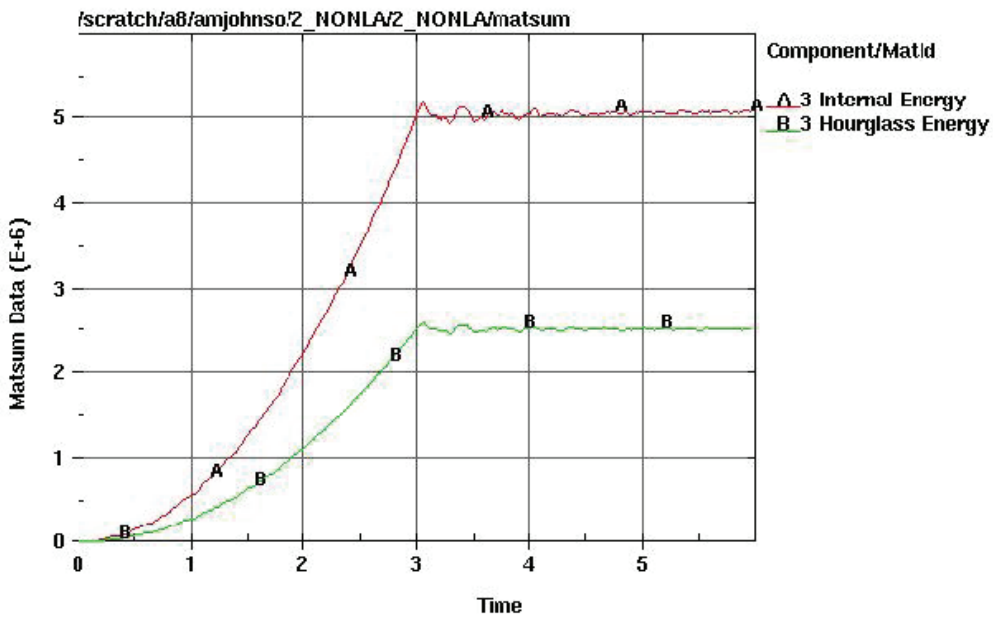


Figure 4e –Analysis 2, rock block internal and hourglass energies

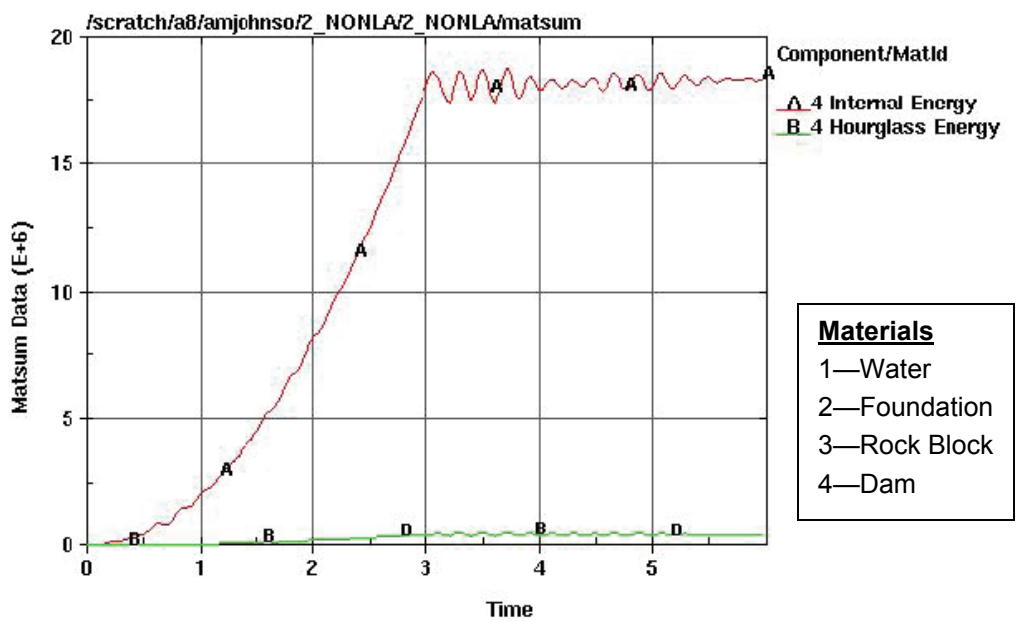


Figure 4f –Analysis 2, dam internal and hourglass energies

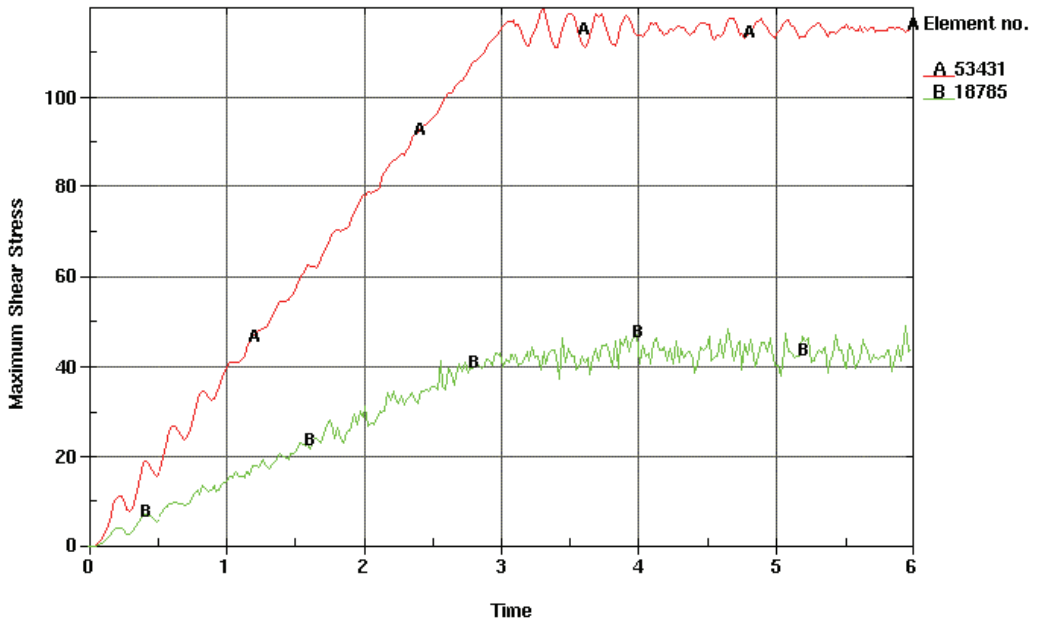


Figure 4g –Analysis 2, max shear stress at right foundation contact near rock block.

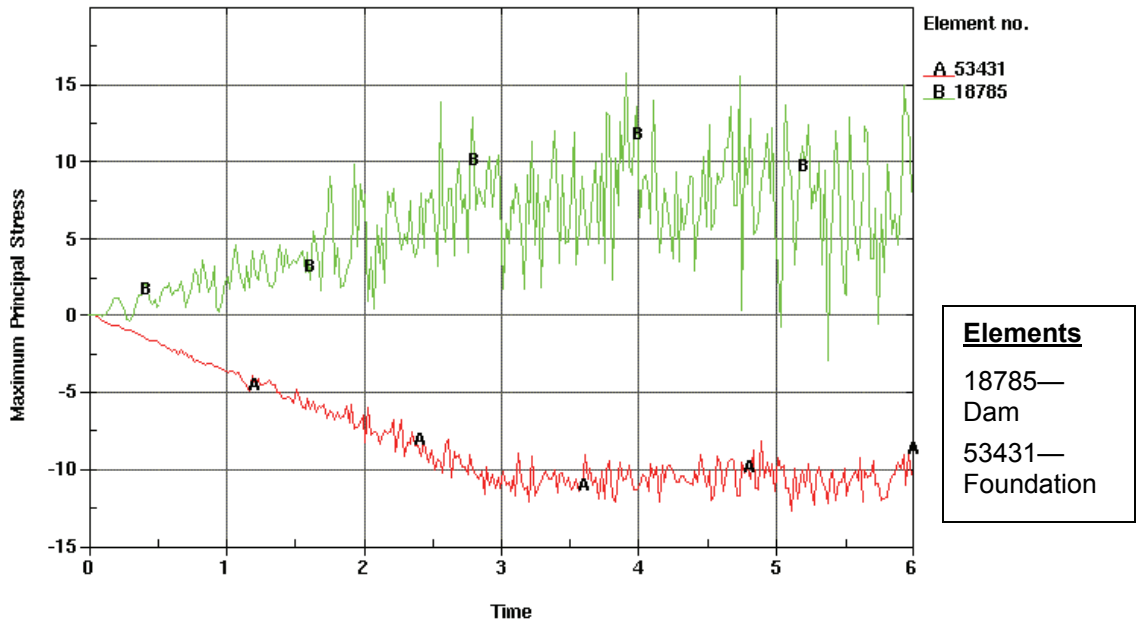


Figure 4h –Analysis 2, max principal stress at right foundation contact near rock block.

ANALYSIS 2a
Analysis characteristics

IHQ (dam)	3
IHQ (foundation and rock block)	3
IHQ (water)	3
QM (dam)	0.10
QM (foundation and rock block)	0.10
QM (water)	0.10
Foundation/dam mesh sizes	fine/coarse
Water/foundation contact	SURFACE_TO_SURFACE
…..notes	
Dam/water contact	SURFACE_TO_SURFACE
…..notes	
Foundation/dam contact	TIED_SURFACE_TO_SURFACE
…..notes	static and dynamic friction = 0.57
Rock block/foundation contact	AUTOMATIC_SURFACE_TO_SURFACE_TIEBREAK
…..notes	
Contraction joints	AUTOMATIC_SURFACE_TO_SURFACE_TIEBREAK
…..notes	static and dynamic friction = 0.57

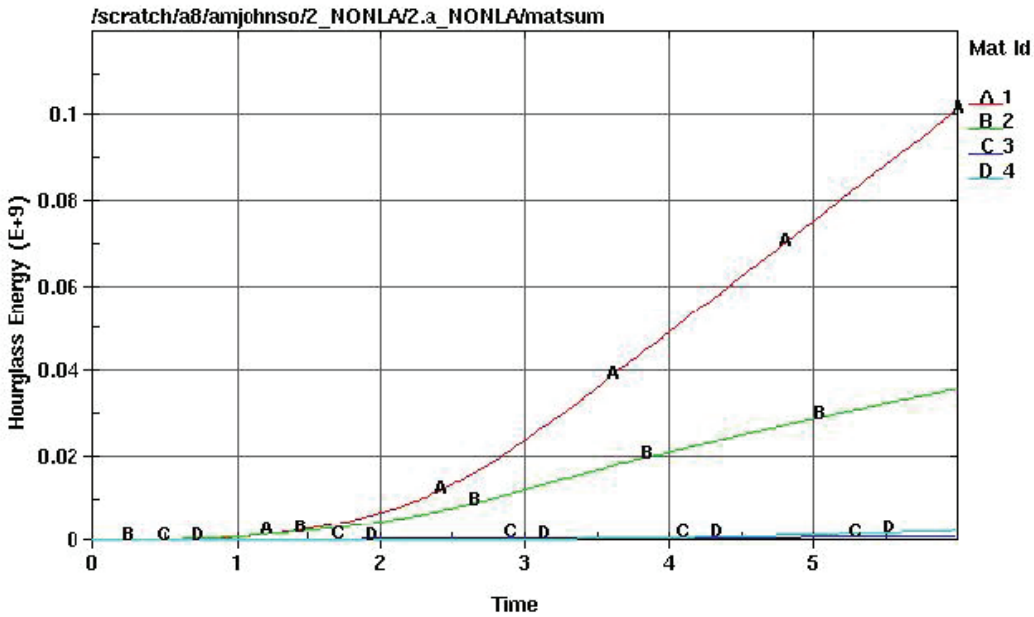


Figure 5a –Analysis 2.a hourglass energy per material

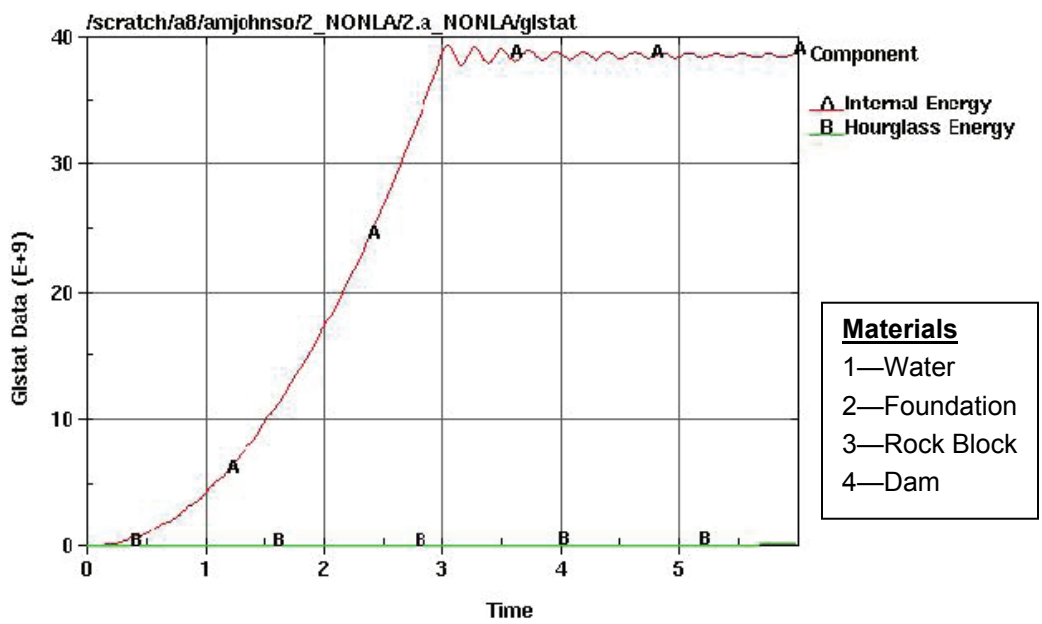


Figure 5b –Analysis 2.a global internal and hourglass energies

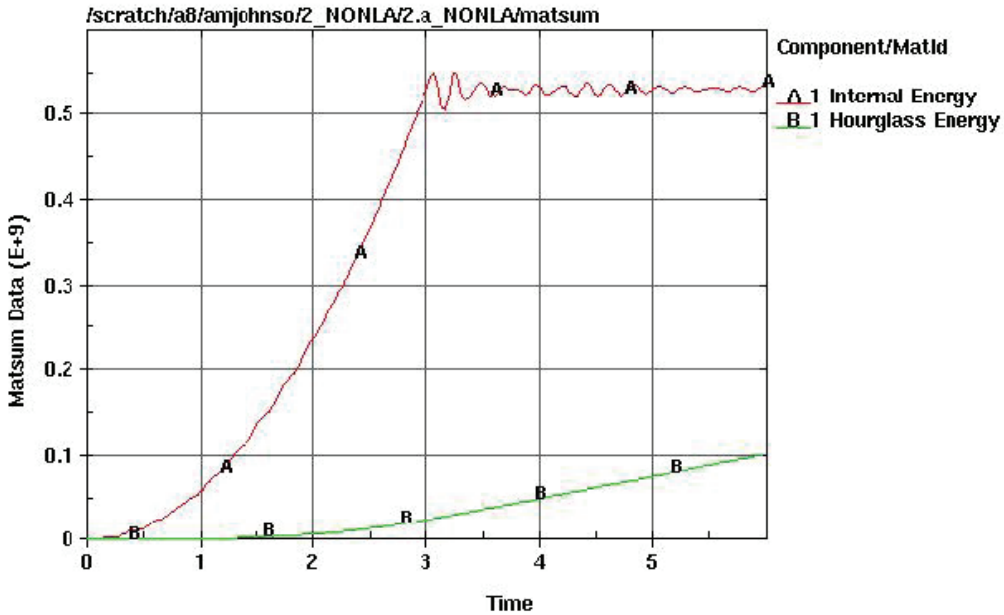


Figure 5c –Analysis 2.a, water, internal and hourglass energies

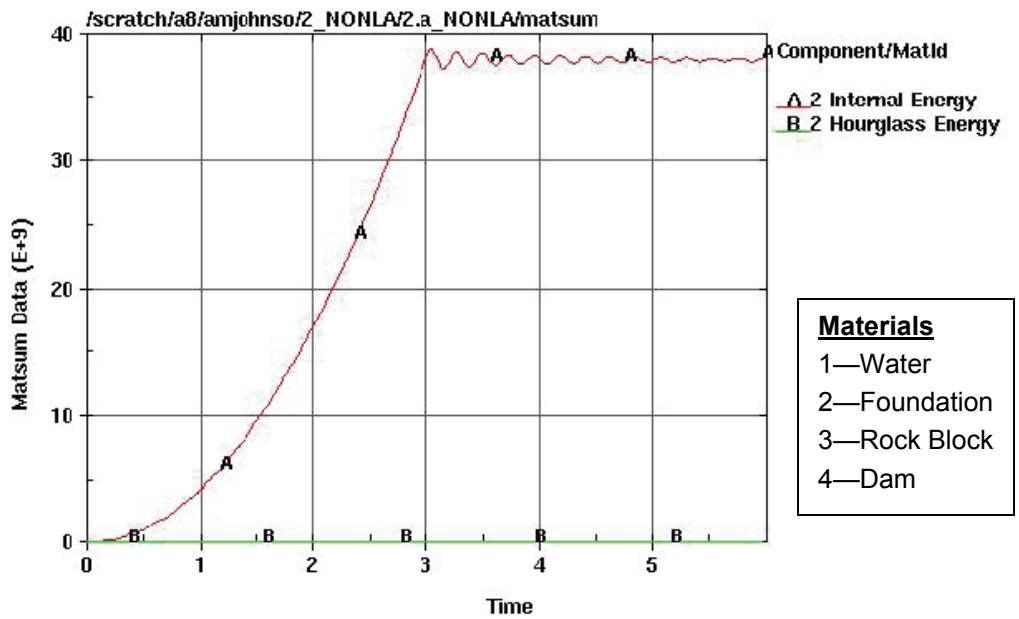


Figure 5d –Analysis 2.a, foundation, internal and hourglass energies

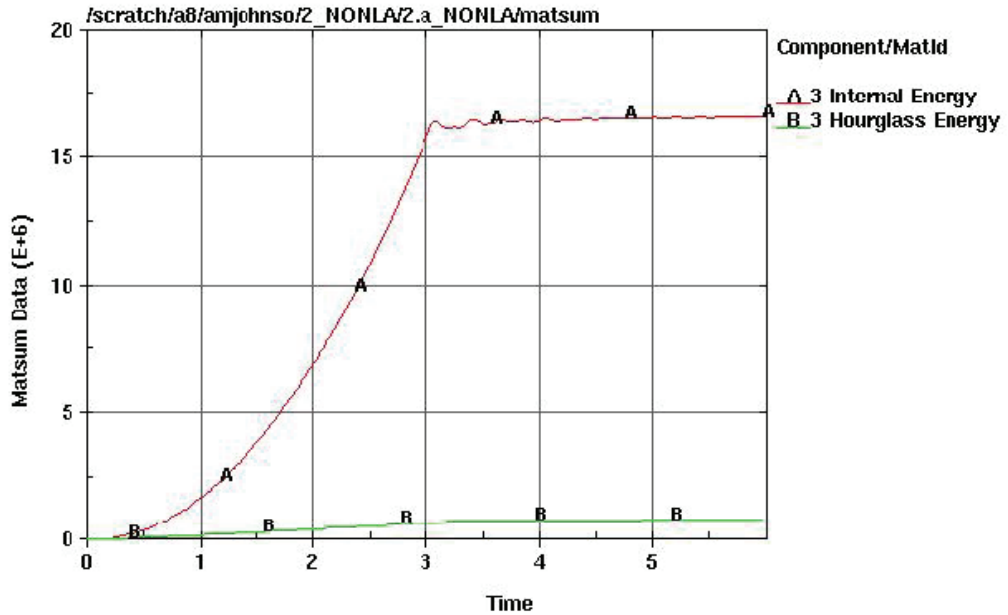


Figure 5e –Analysis 2.a, rock block internal and hourglass energies

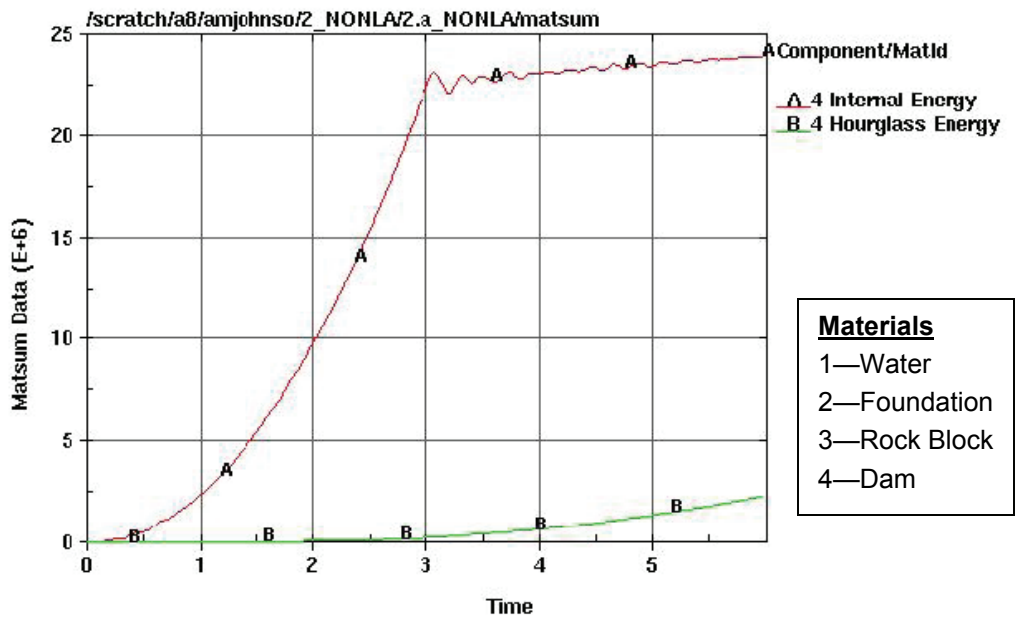


Figure 5f –Analysis 2.a, dam internal and hourglass energies

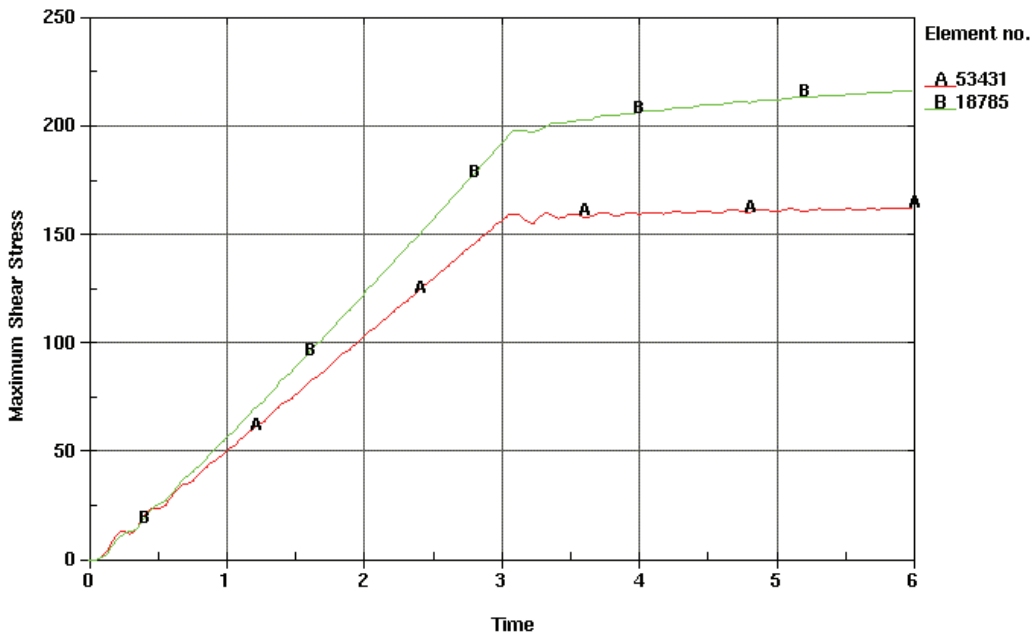


Figure 5g –Analysis 2.a, max shear stress at right foundation contact near rock block.

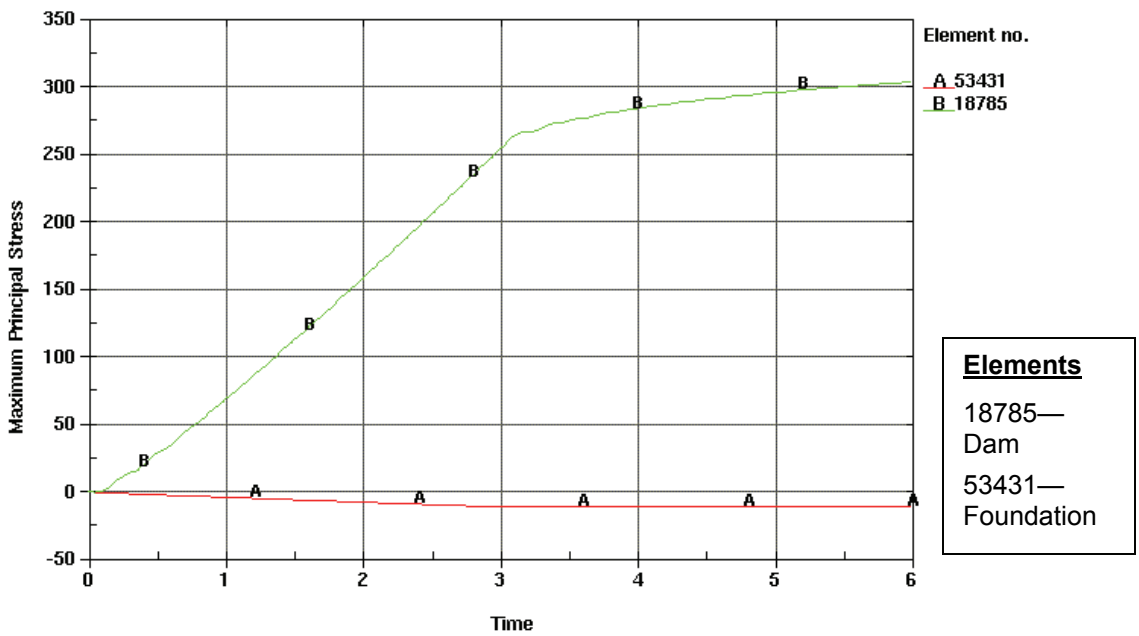


Figure 5h –Analysis 2.a, max principal stress at right foundation contact near rock block.

ANALYSIS 3
Analysis characteristics

IHQ (dam)	5
IHQ (foundation and rock block)	5
IHQ (water)	5
QM (dam)	0.15
QM (foundation and rock block)	0.15
QM (water)	0.15
Foundation/dam mesh sizes	fine/coarse
Water/foundation contact	SURFACE_TO_SURFACE
…..notes	
Dam/water contact	SURFACE_TO_SURFACE
…..notes	
Foundation/dam contact	TIED_SURFACE_TO_SURFACE
…..notes	static and dynamic friction = 0.57
Rock block/foundation contact	AUTOMATIC_SURFACE_TO_SURFACE_TIEBREAK
…..notes	
Contraction joints	AUTOMATIC_SURFACE_TO_SURFACE_TIEBREAK
…..notes	static and dynamic friction = 0.57

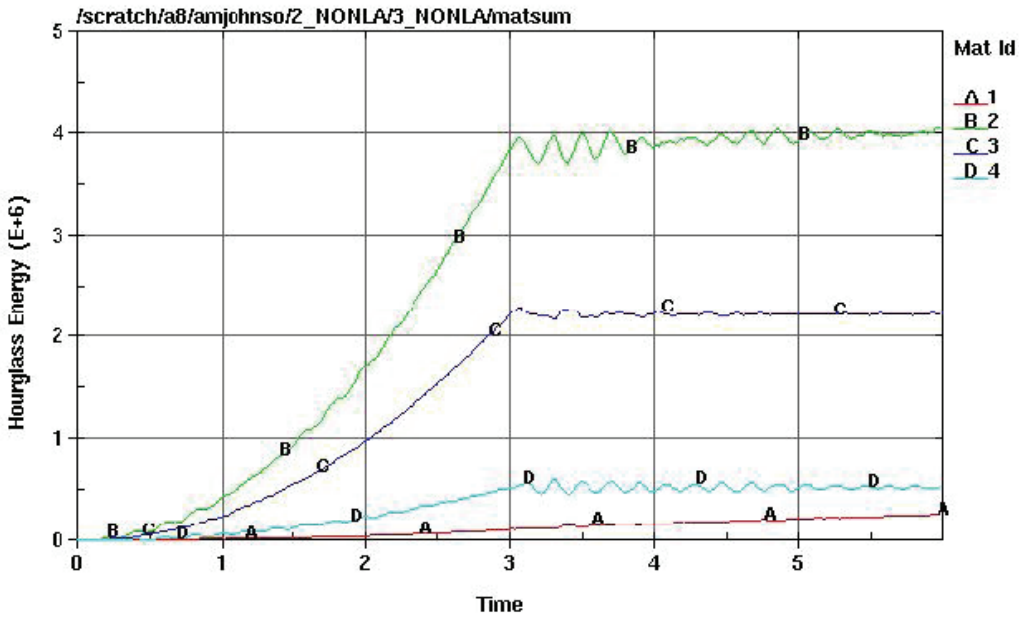


Figure 6a –Analysis 3 hourglass energy per material

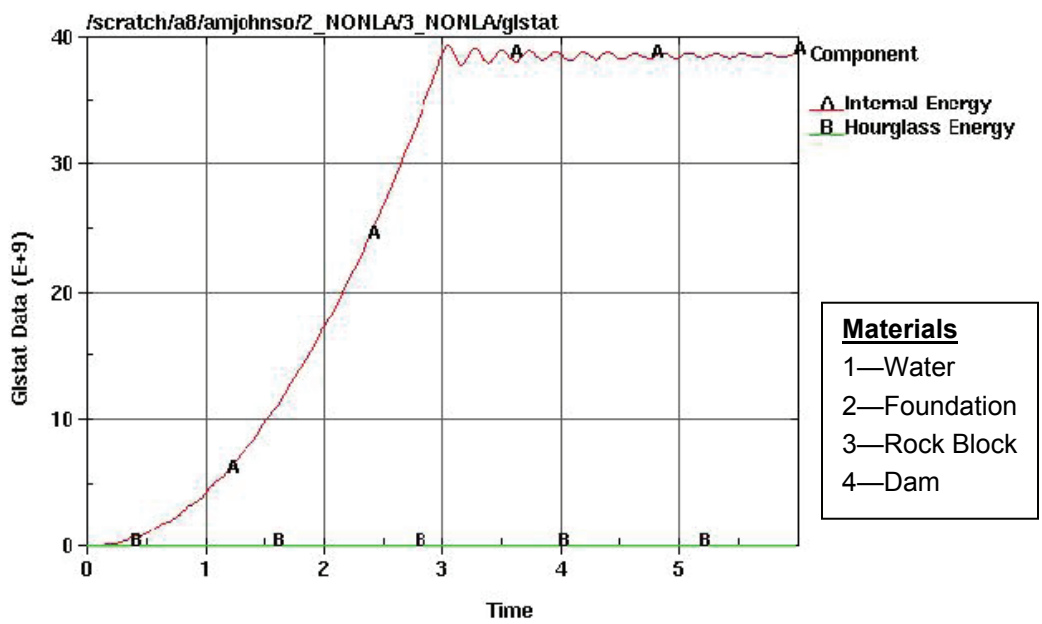


Figure 6b –Analysis 3 global internal and hourglass energies

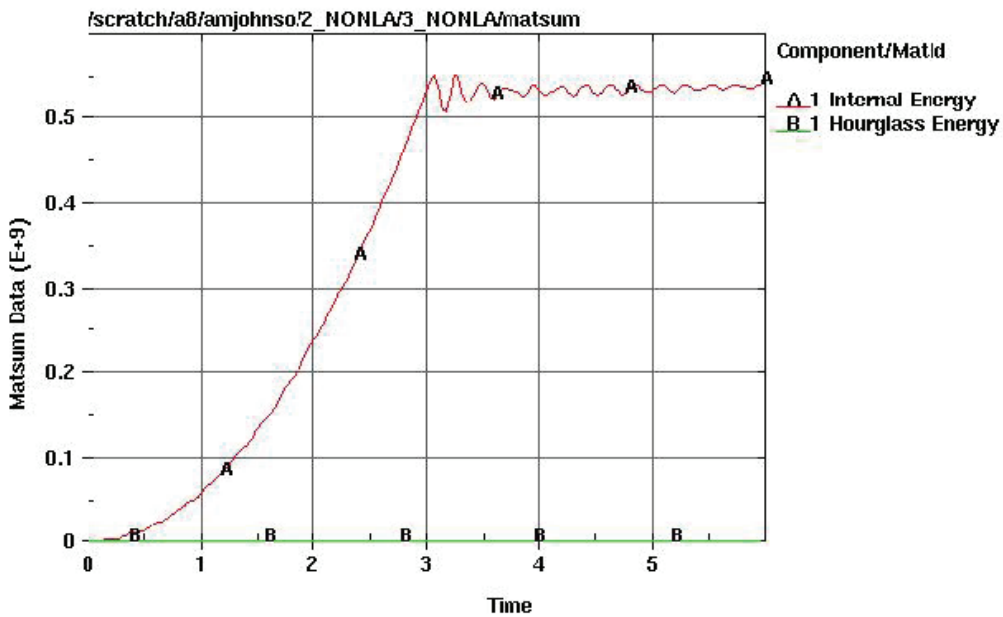


Figure 6c –Analysis 3, water, internal and hourglass energies

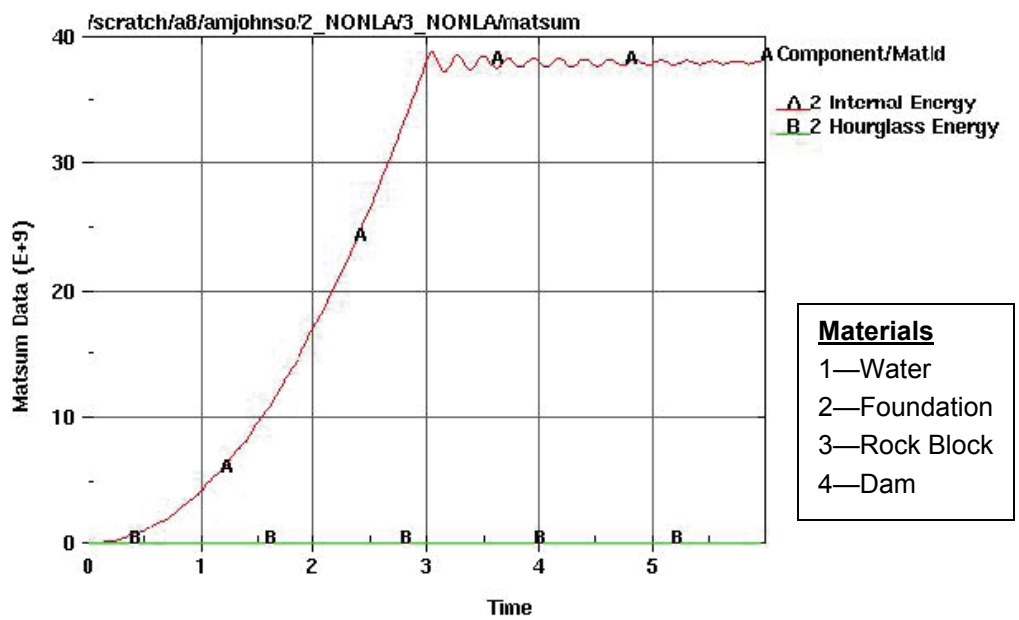


Figure 6d –Analysis 3, foundation, internal and hourglass energies

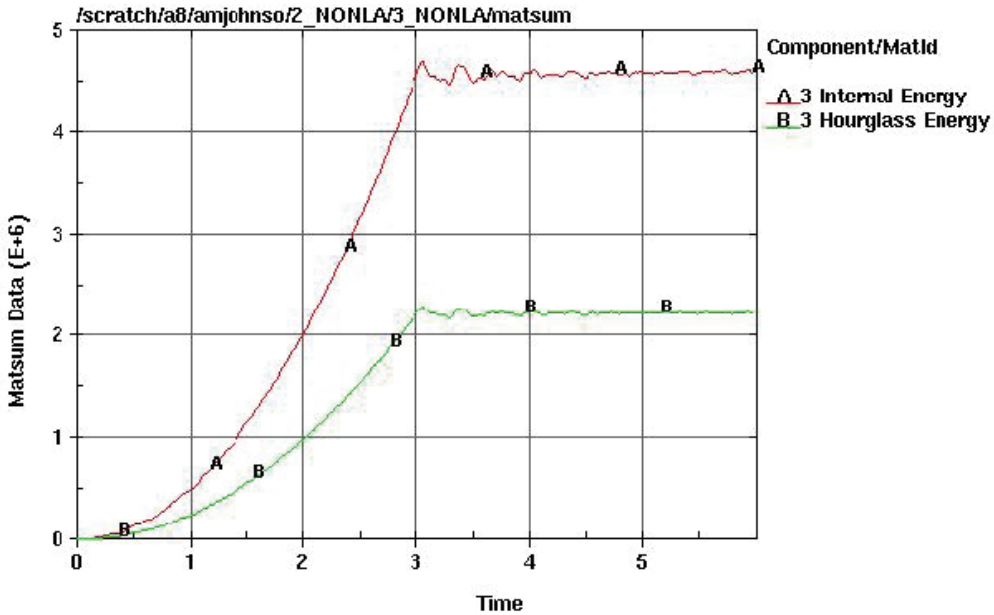


Figure 6e –Analysis 3, rock block internal and hourglass energies

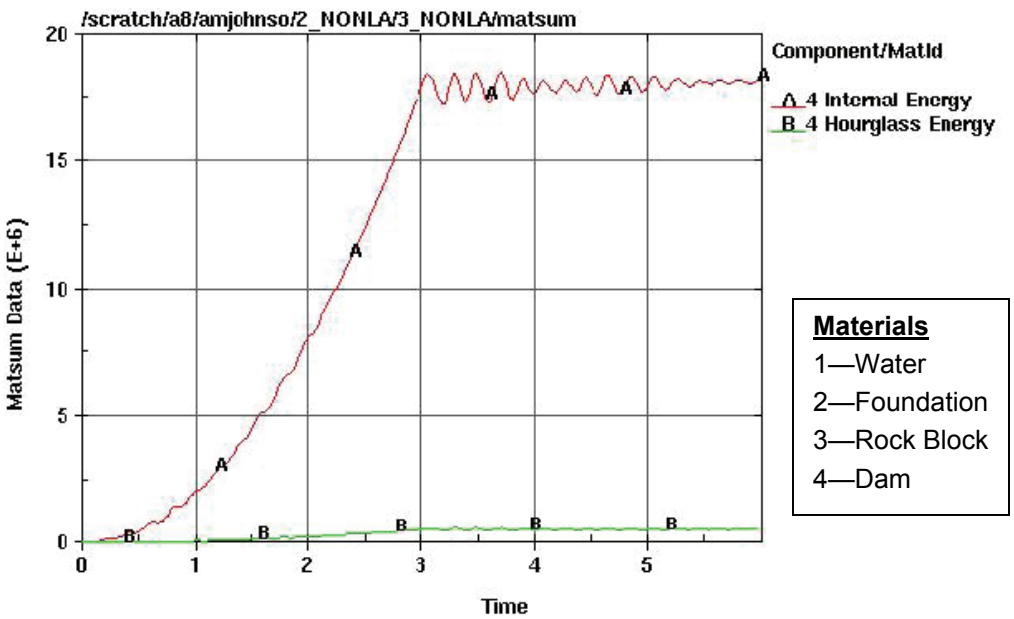


Figure 6f –Analysis 3, dam internal and hourglass energies

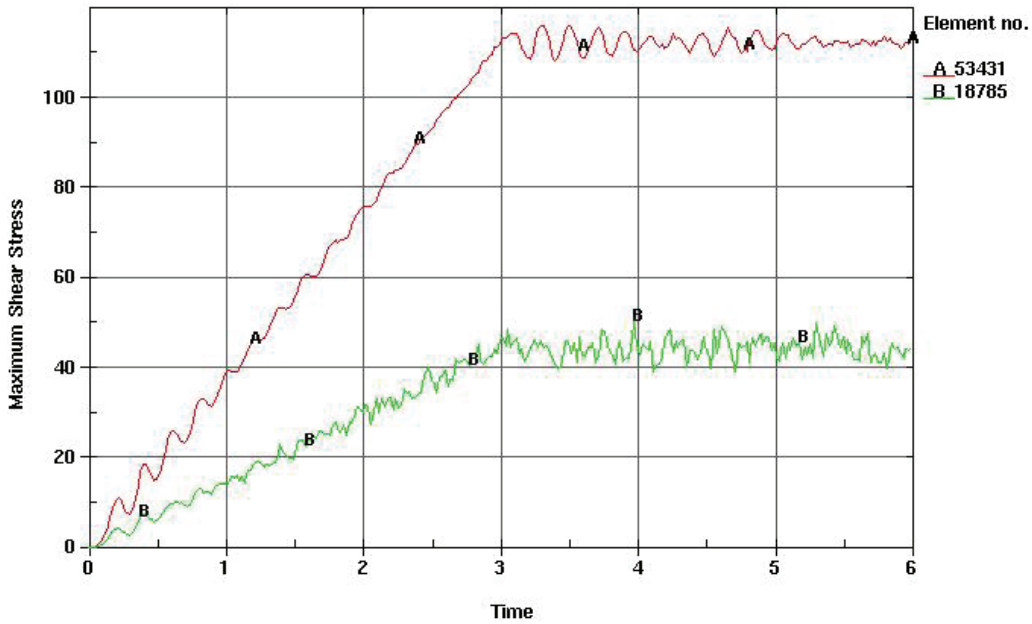


Figure 6g –Analysis 3, max shear stress at right foundation contact near rock block.

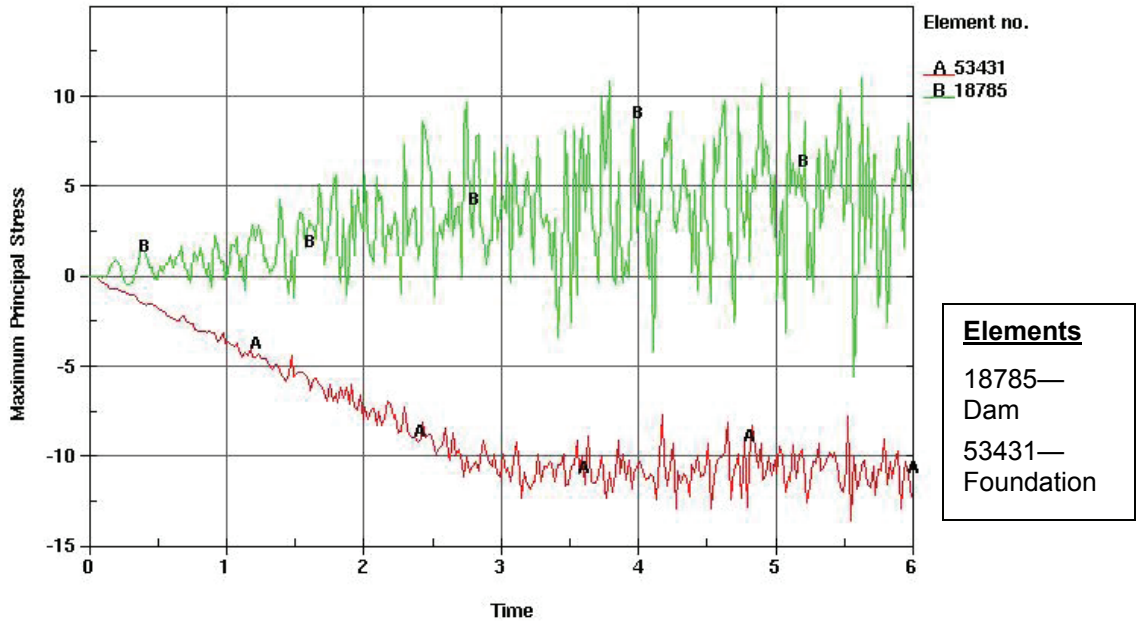


Figure 6h –Analysis 3, max principal stress at right foundation contact near rock block.

ANALYSIS 3a
Analysis characteristics

IHQ (dam)	3
IHQ (foundation and rock block)	3
IHQ (water)	3
QM (dam)	0.15
QM (foundation and rock block)	0.15
QM (water)	0.15
Foundation/dam mesh sizes	fine/coarse
Water/foundation contact	SURFACE_TO_SURFACE
…..notes	
Dam/water contact	SURFACE_TO_SURFACE
…..notes	
Foundation/dam contact	TIED_SURFACE_TO_SURFACE
…..notes	static and dynamic friction = 0.57
Rock block/foundation contact	AUTOMATIC_SURFACE_TO_SURFACE_TIEBREAK
…..notes	
Contraction joints	AUTOMATIC_SURFACE_TO_SURFACE_TIEBREAK
…..notes	static and dynamic friction = 0.57

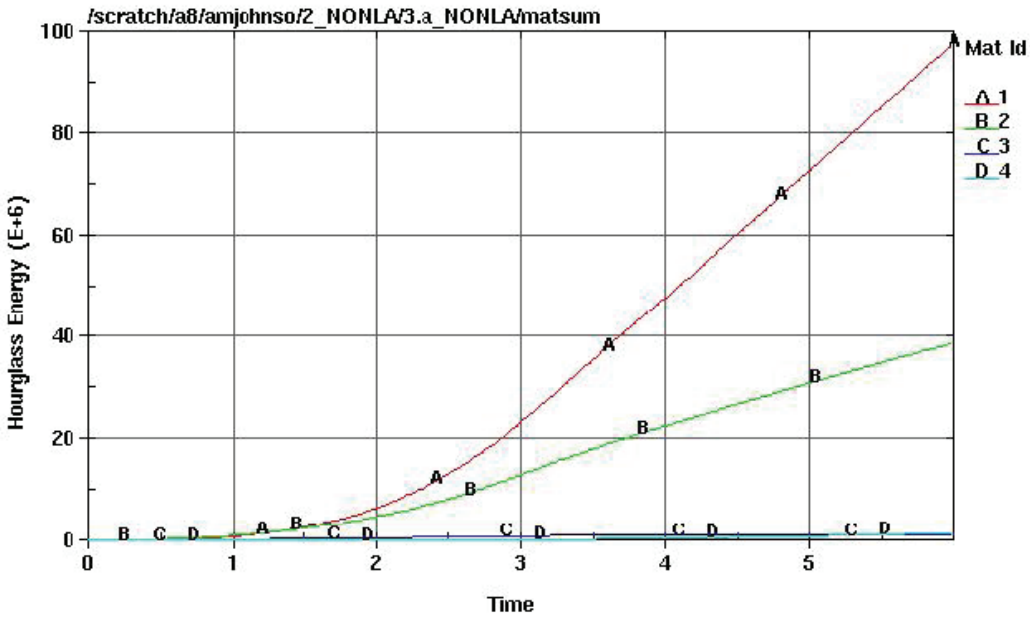


Figure 7a –Analysis 3.a hourglass energy per material

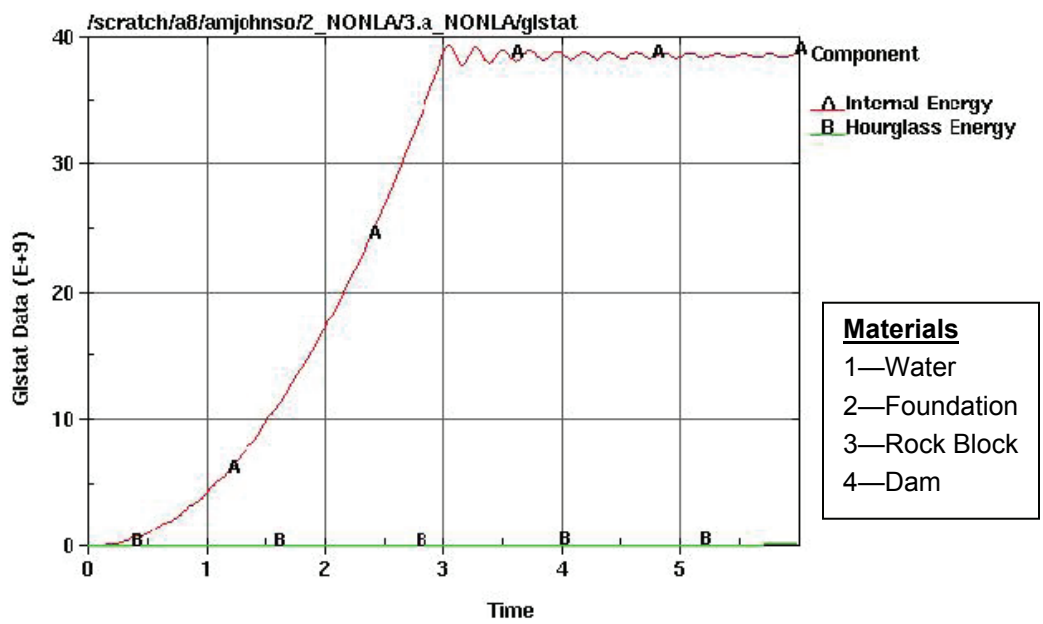


Figure 7b –Analysis 3.a global internal and hourglass energies

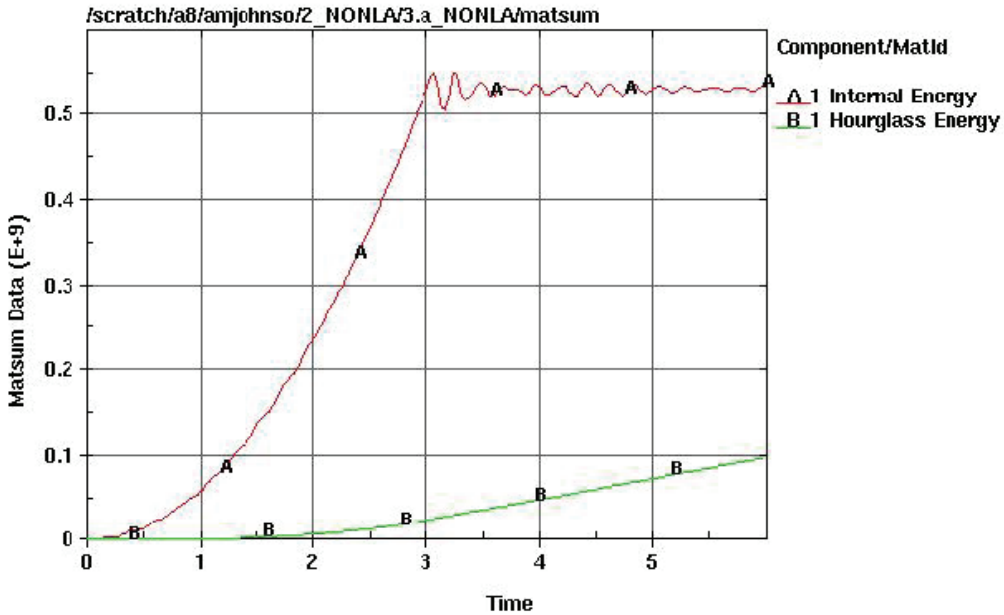


Figure 7c –Analysis 3.a, water, internal and hourglass energies

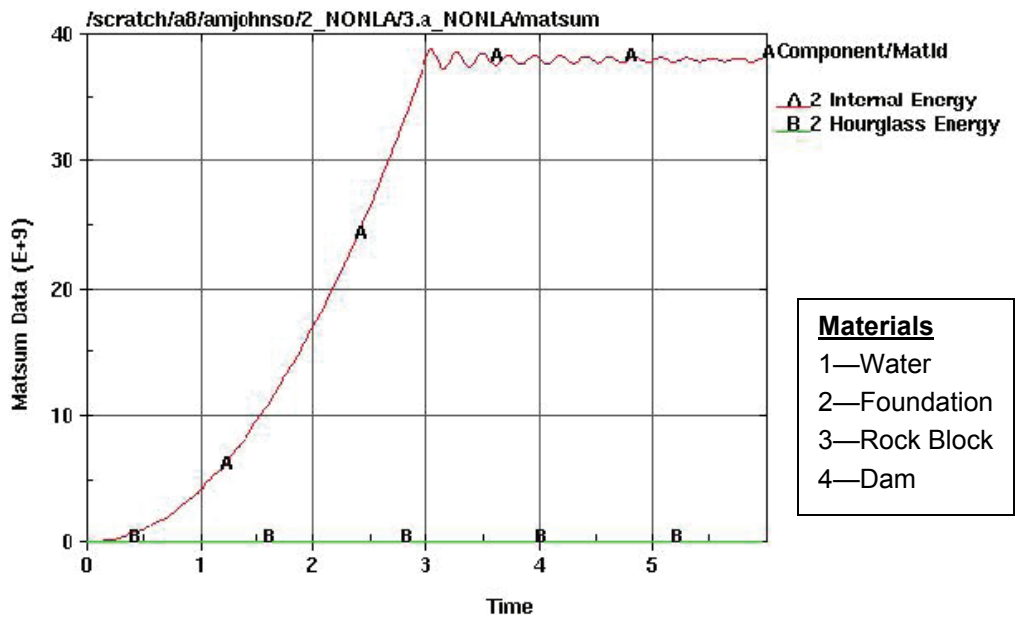


Figure 7d –Analysis 3.a, foundation, internal and hourglass energies

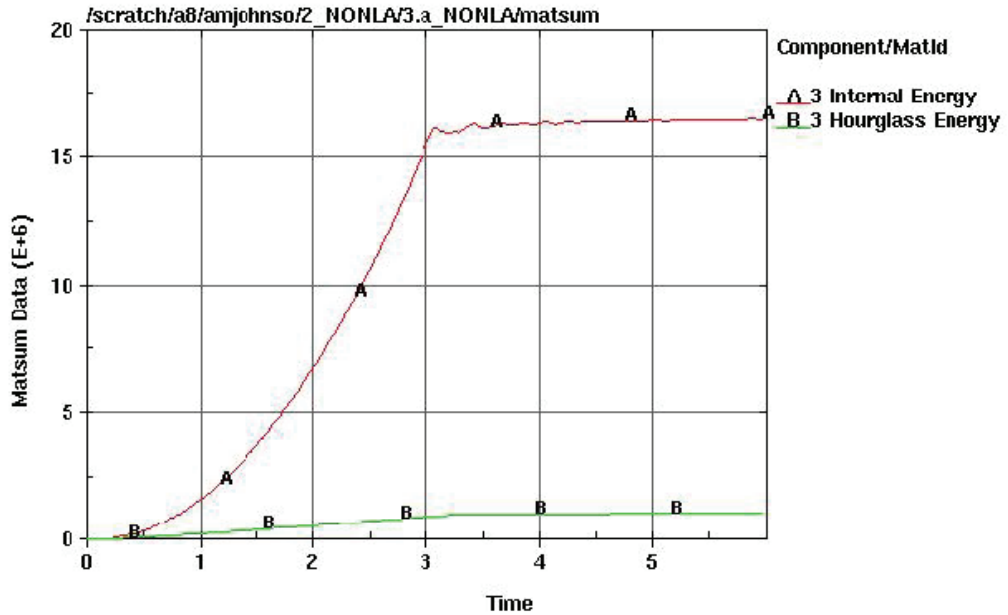


Figure 7e –Analysis 3.a, rock block internal and hourglass energies

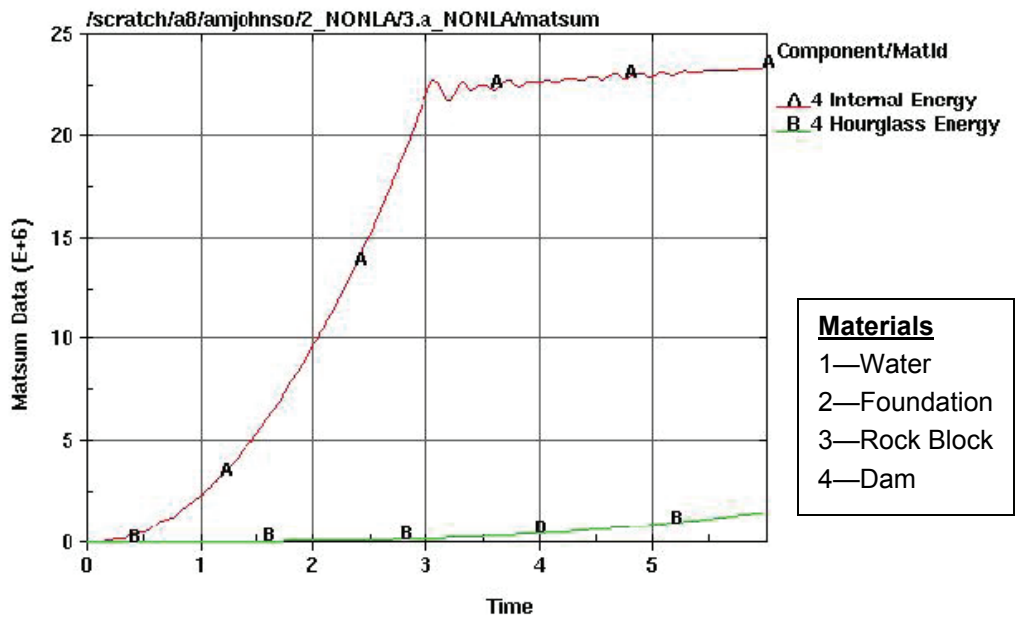


Figure 7f –Analysis 3.a, dam internal and hourglass energies

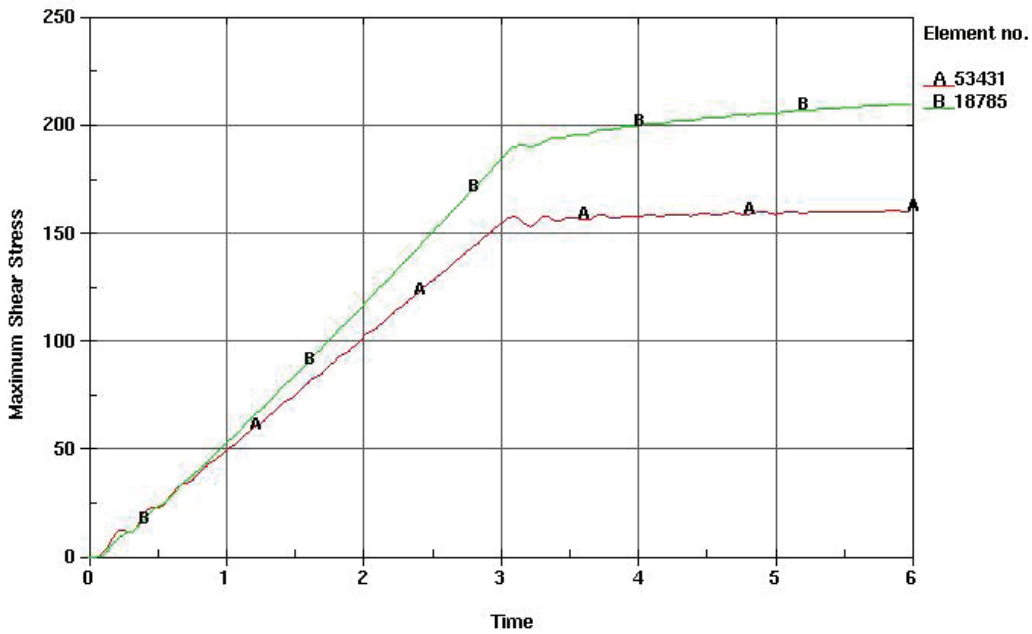


Figure 7g –Analysis 3.a, max shear stress at right foundation contact near rock block.

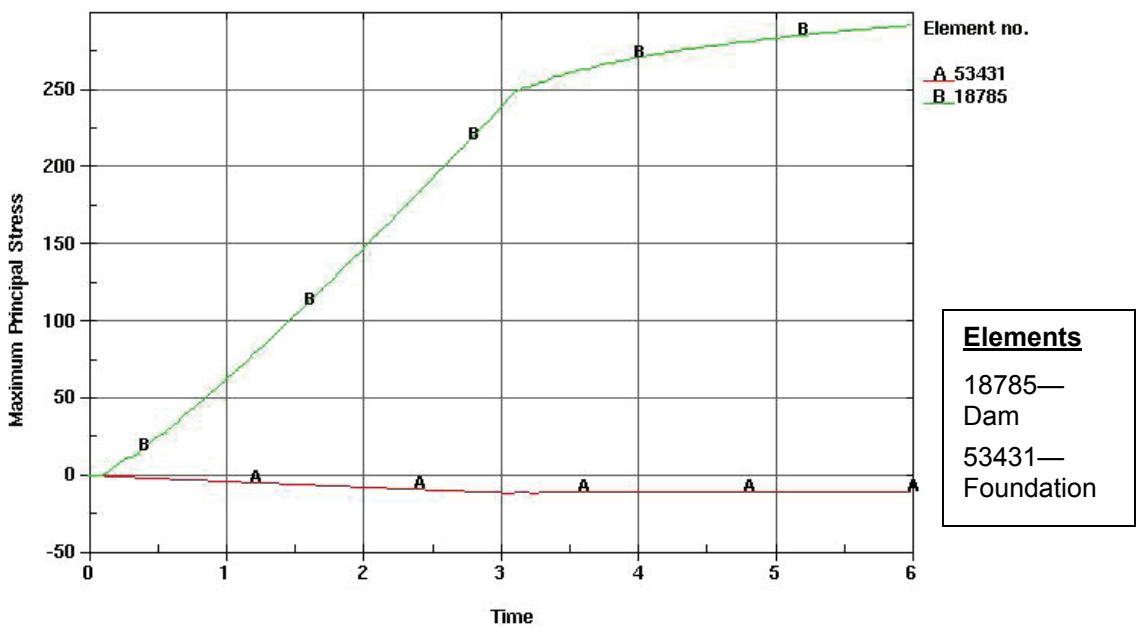


Figure 7h –Analysis 3.a, max principal stress at right foundation contact near rock block.

ANALYSIS 4
Analysis characteristics

IHQ (dam)	5
IHQ (foundation and rock block)	5
IHQ (water)	5
QM (dam)	0.10
QM (foundation and rock block)	0.10
QM (water)	0.10
Foundation/dam mesh sizes	Coarse/fine
Water/foundation contact	SURFACE_TO_SURFACE
…..notes	
Dam/water contact	SURFACE_TO_SURFACE
…..notes	
Foundation/dam contact	TIED_SURFACE_TO_SURFACE
…..notes	static and dynamic friction = 0.57
Rock block/foundation contact	AUTOMATIC_SURFACE_TO_SURFACE_TIEBREAK
…..notes	
Contraction joints	AUTOMATIC_SURFACE_TO_SURFACE_TIEBREAK
…..notes	static and dynamic friction = 0.57

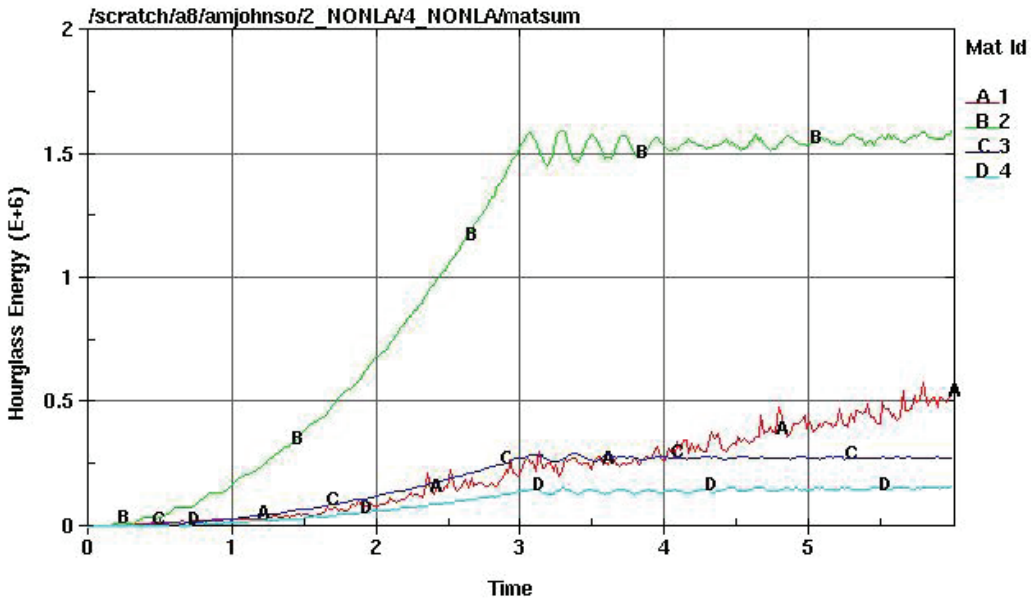


Figure 8a –Analysis 4 hourglass energy per material

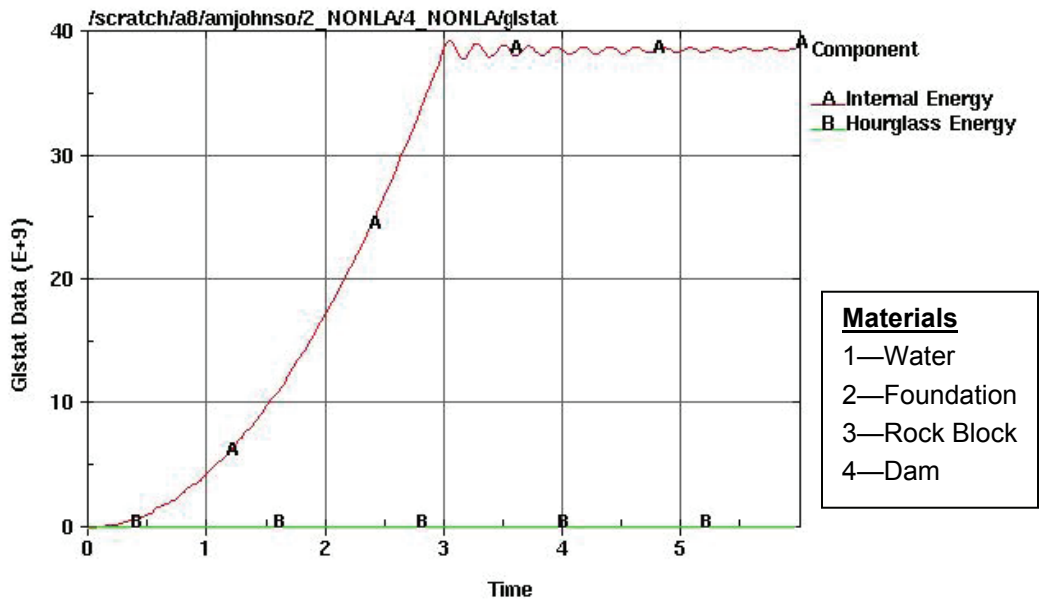


Figure 8b –Analysis 4 global internal and hourglass energies

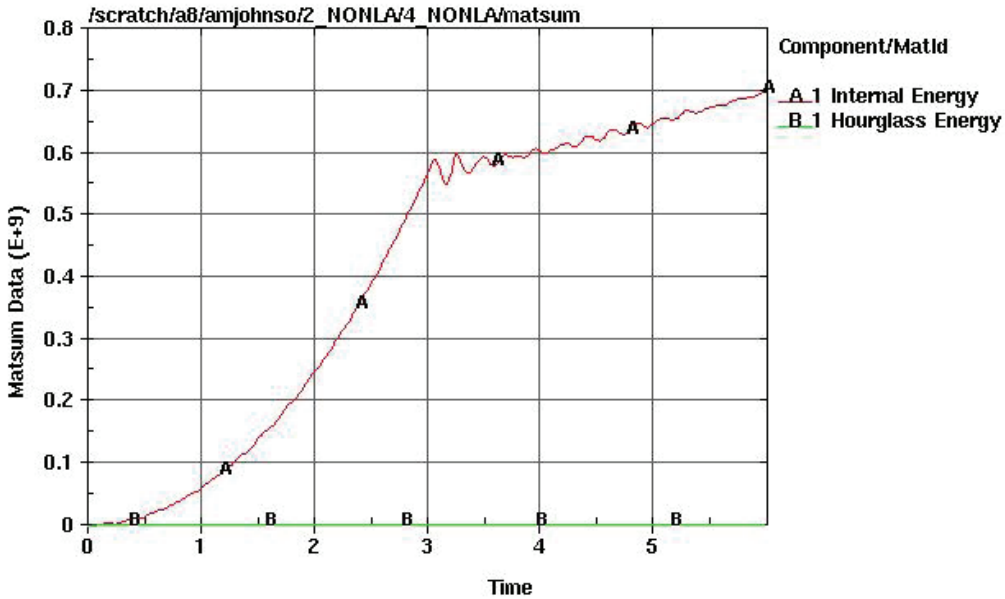


Figure 8c –Analysis 4, water, internal and hourglass energies

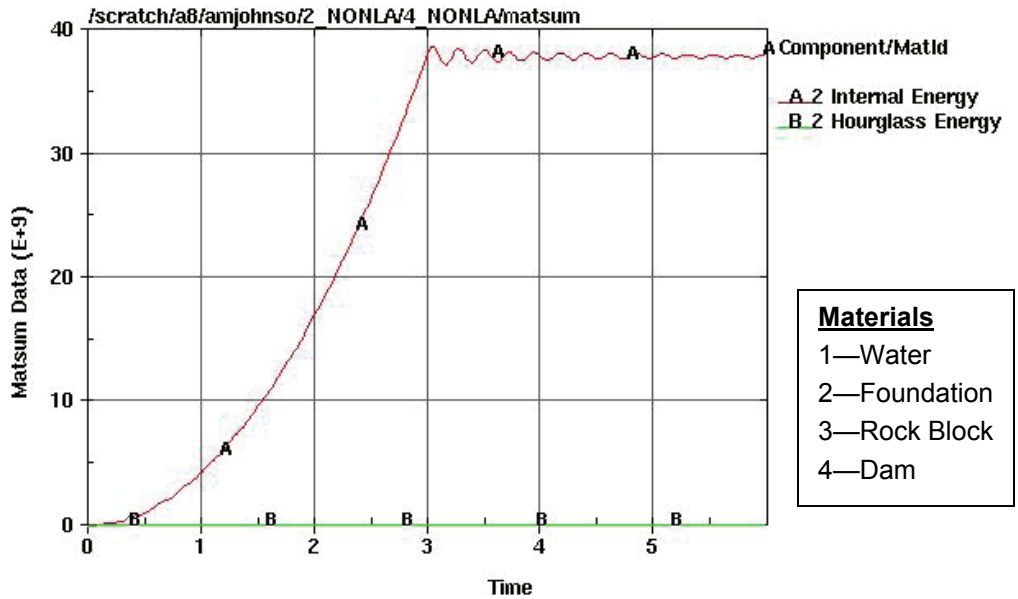


Figure 8d –Analysis 4, foundation, internal and hourglass energies

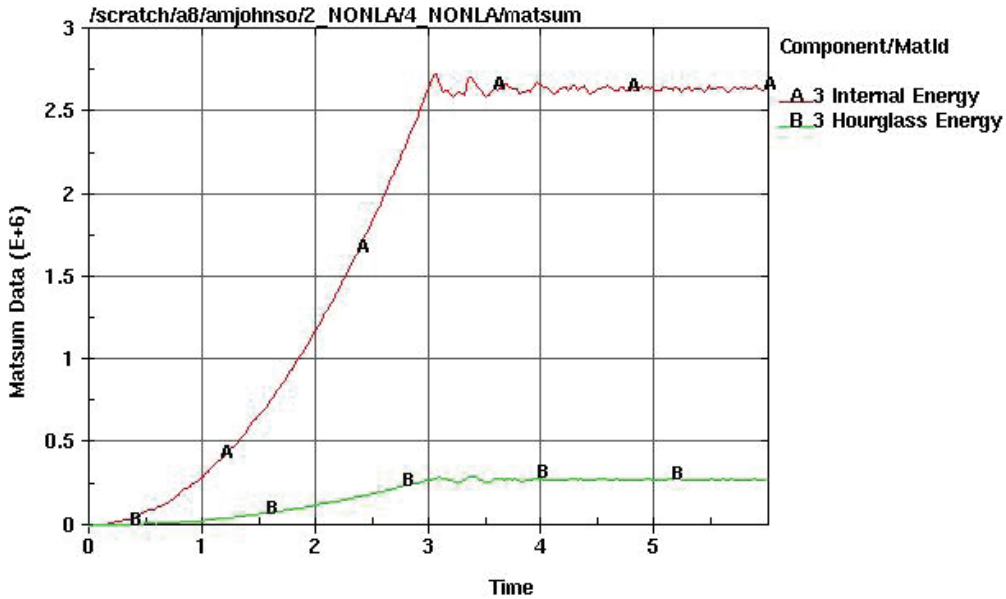


Figure 8e –Analysis 4, rock block internal and hourglass energies

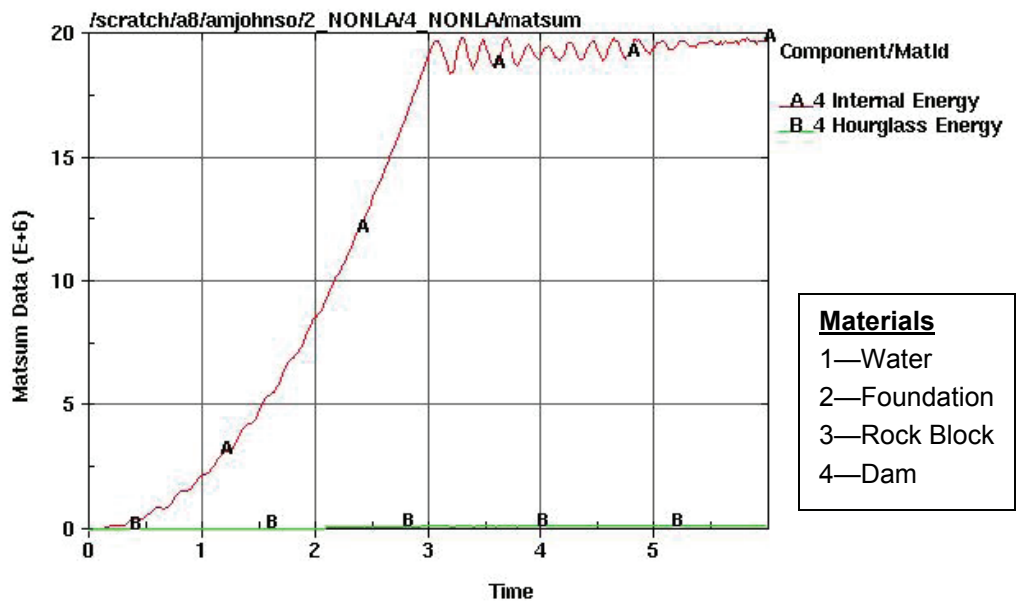


Figure 8f –Analysis 4, dam internal and hourglass energies

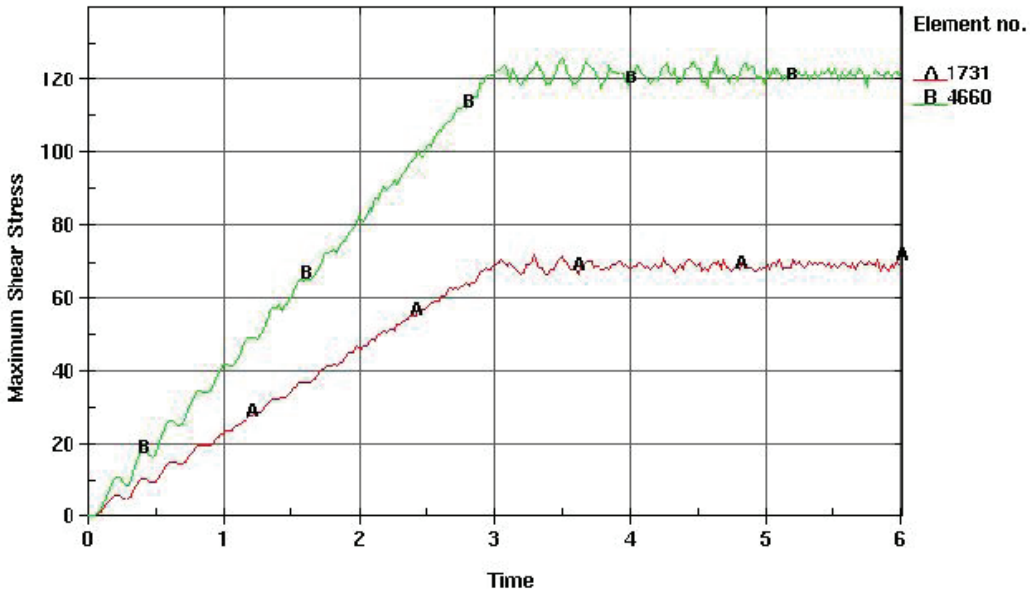


Figure 8g –Analysis 4, max shear stress at right foundation contact near rock block.

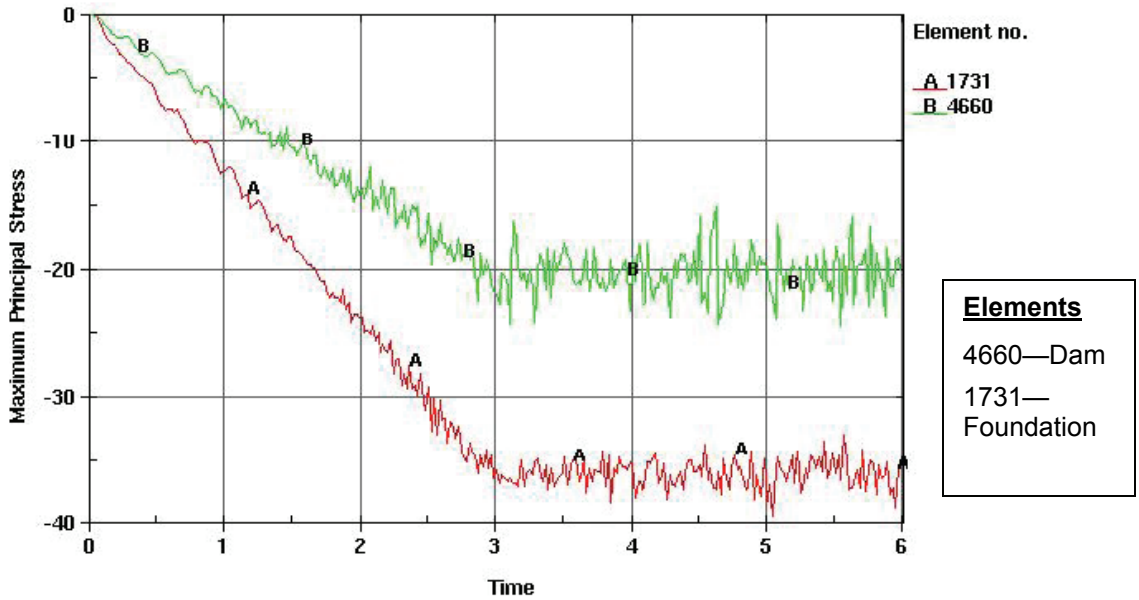


Figure 8h –Analysis 4, max principal stress at right foundation contact near rock block.

ANALYSIS 4.1
Analysis characteristics

IHQ (dam)	5
IHQ (foundation and rock block)	5
IHQ (water)	1
QM (dam)	0.10
QM (foundation and rock block)	0.10
QM (water)	0.0001
Foundation/dam mesh sizes	Coarse/fine
Water/foundation contact	SURFACE_TO_SURFACE
…..notes	
Dam/water contact	SURFACE_TO_SURFACE
…..notes	
Foundation/dam contact	TIED_SURFACE_TO_SURFACE
…..notes	static and dynamic friction = 0.57
Rock block/foundation contact	AUTOMATIC_SURFACE_TO_SURFACE_TIEBREAK
…..notes	
Contraction joints	AUTOMATIC_SURFACE_TO_SURFACE_TIEBREAK
…..notes	static and dynamic friction = 0.57

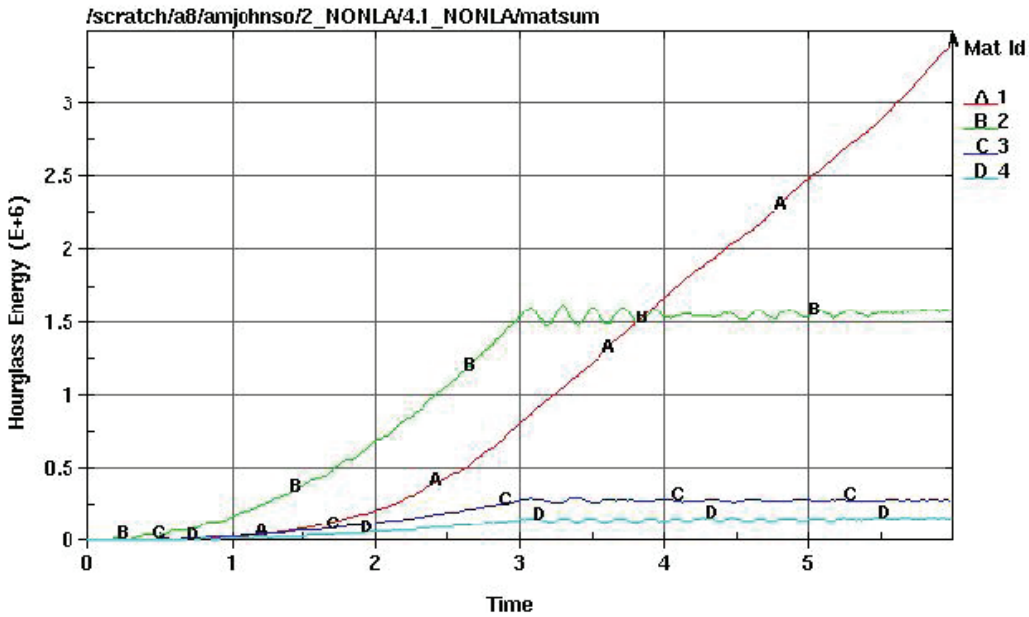


Figure 9a –Analysis 4.1 hourglass energy per material

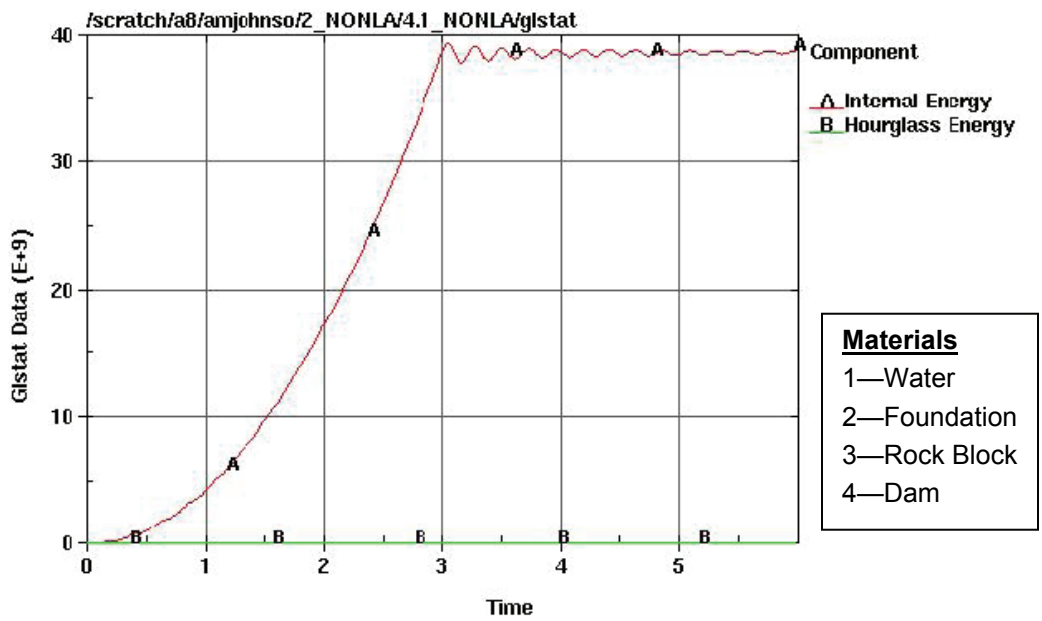


Figure 9b –Analysis 4.1 global internal and hourglass energies

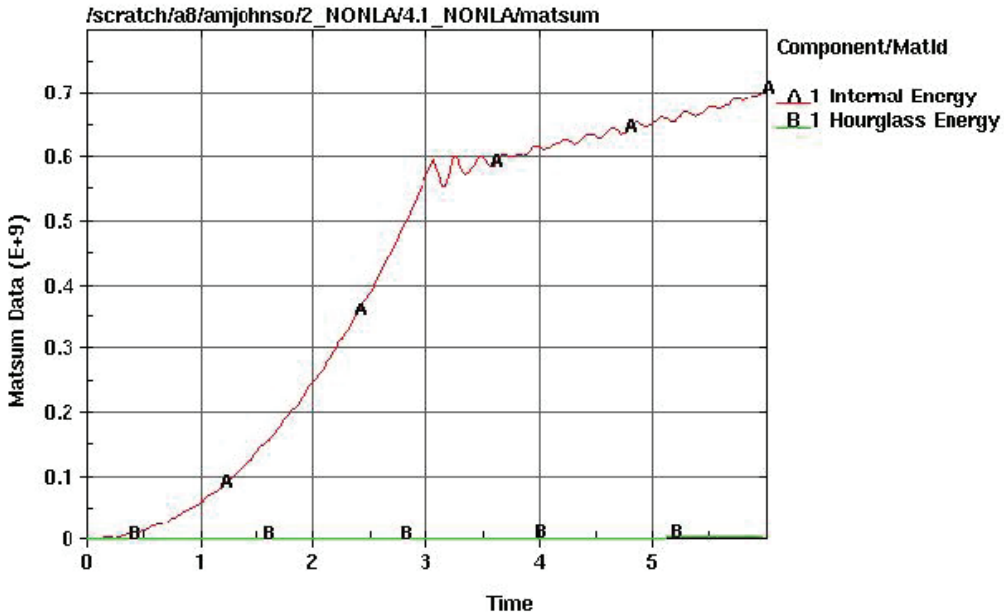


Figure 9c –Analysis 4.1, water, internal and hourglass energies

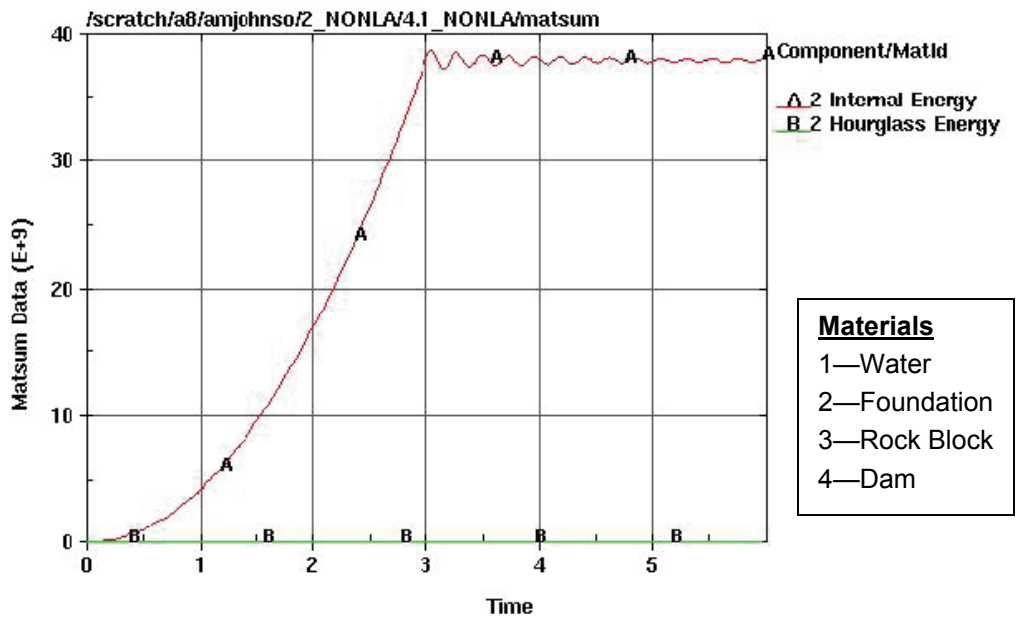


Figure 9d –Analysis 4.1, foundation, internal and hourglass energies

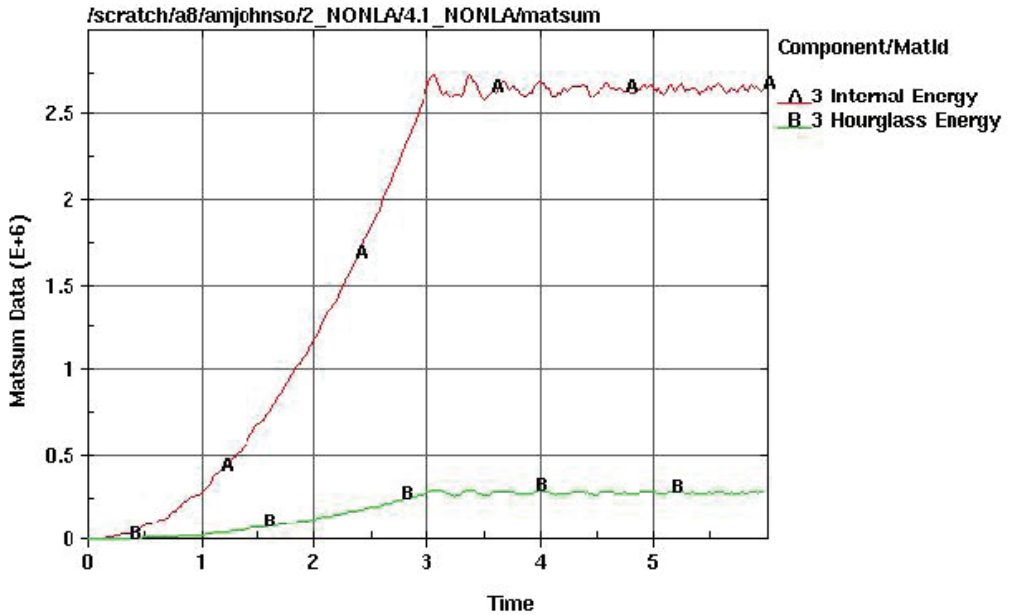


Figure 9e –Analysis 4.1, rock block internal and hourglass energies

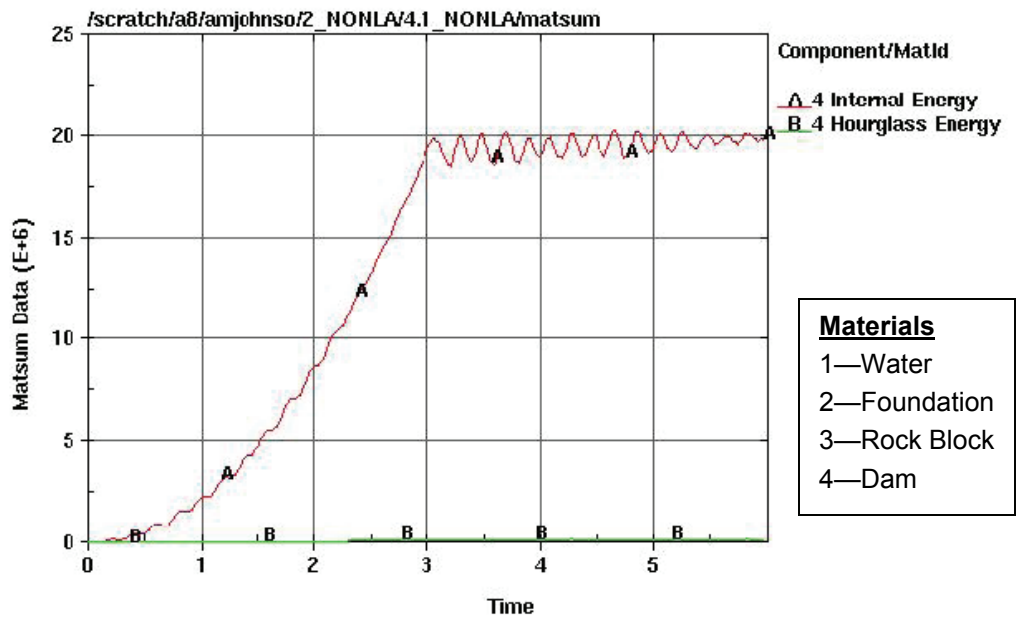


Figure 9f –Analysis 4.1, dam internal and hourglass energies

ANALYSIS 5
Analysis characteristics

IHQ (dam)	5
IHQ (foundation and rock block)	5
IHQ (water)	5
QM (dam)	0.10
QM (foundation and rock block)	0.10
QM (water)	0.10
Foundation/dam mesh sizes	Fine/fine
Water/foundation contact	SURFACE_TO_SURFACE
…..notes	
Dam/water contact	SURFACE_TO_SURFACE
…..notes	
Foundation/dam contact	TIED_SURFACE_TO_SURFACE
…..notes	static and dynamic friction = 0.57
Rock block/foundation contact	AUTOMATIC_SURFACE_TO_SURFACE_TIEBREAK
…..notes	
Contraction joints	AUTOMATIC_SURFACE_TO_SURFACE_TIEBREAK
…..notes	static and dynamic friction = 0.57

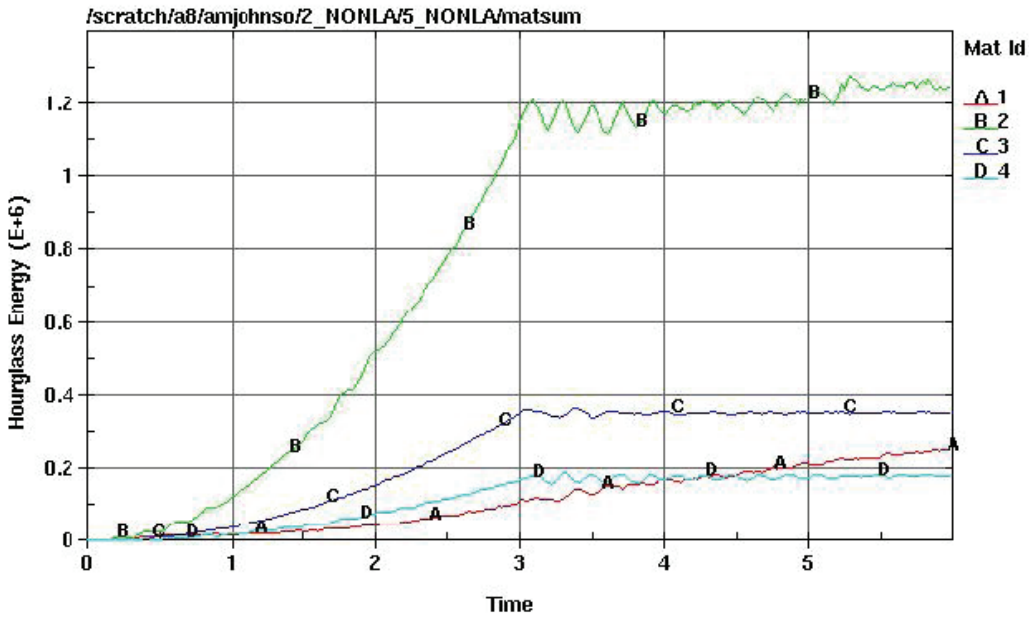


Figure 10a –Analysis 5 hourglass energy per material

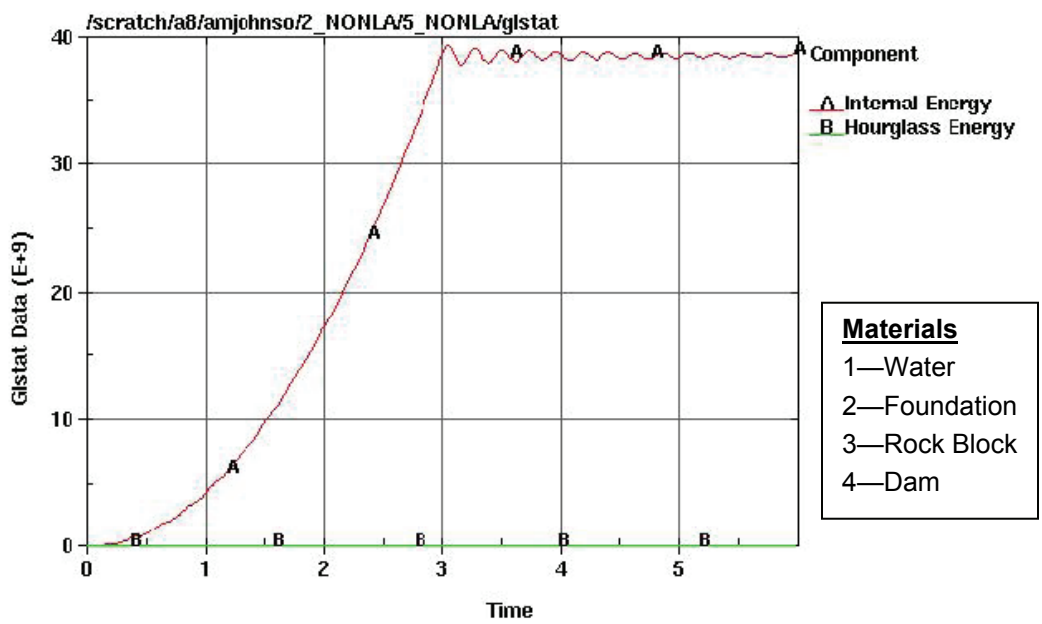


Figure 10b –Analysis 5 global internal and hourglass energies

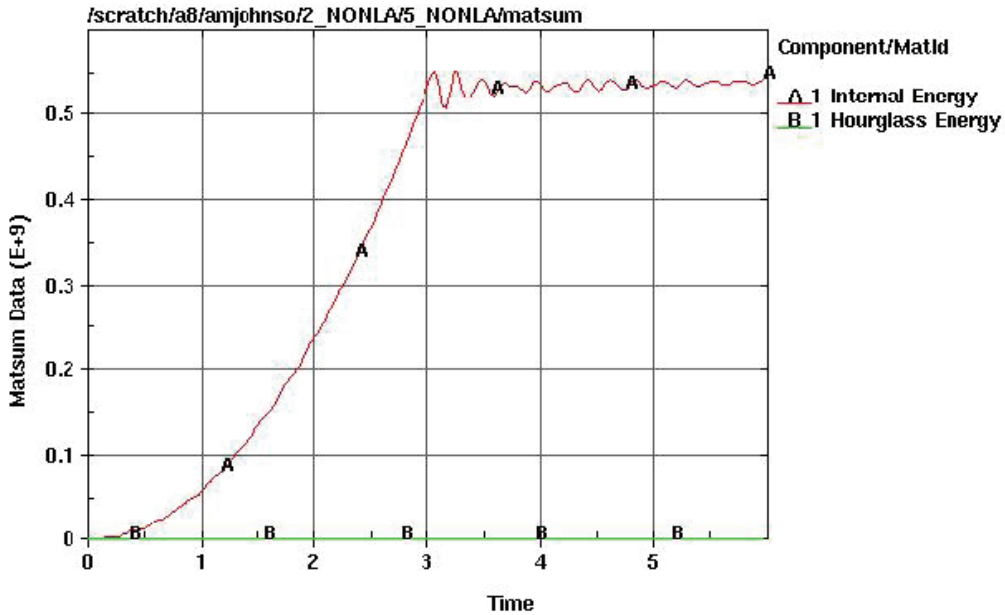


Figure 10c –Analysis 5, water, internal and hourglass energies

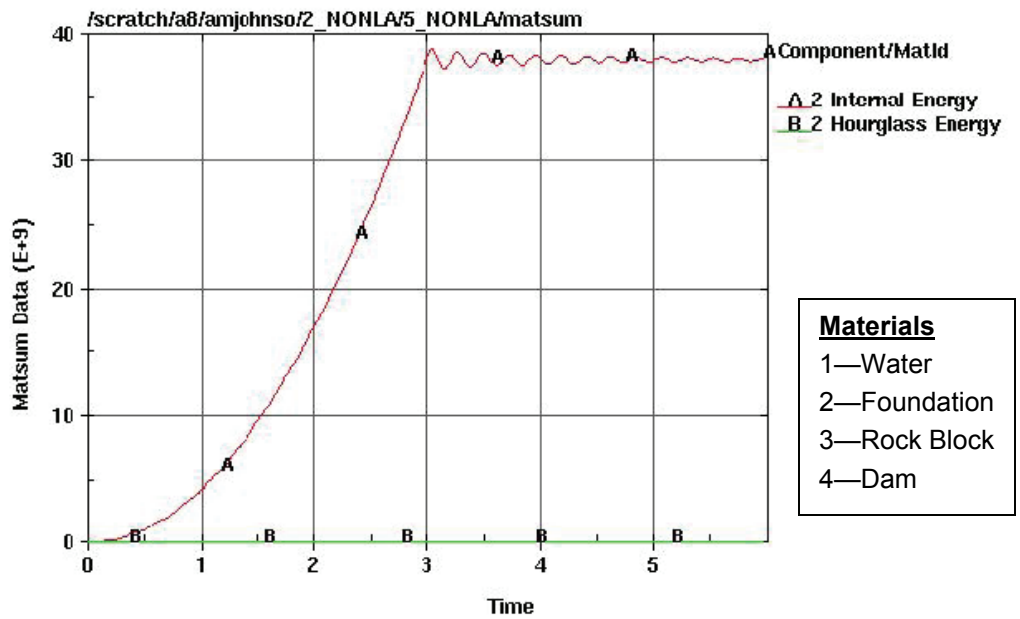


Figure 10d –Analysis 5, foundation, internal and hourglass energies

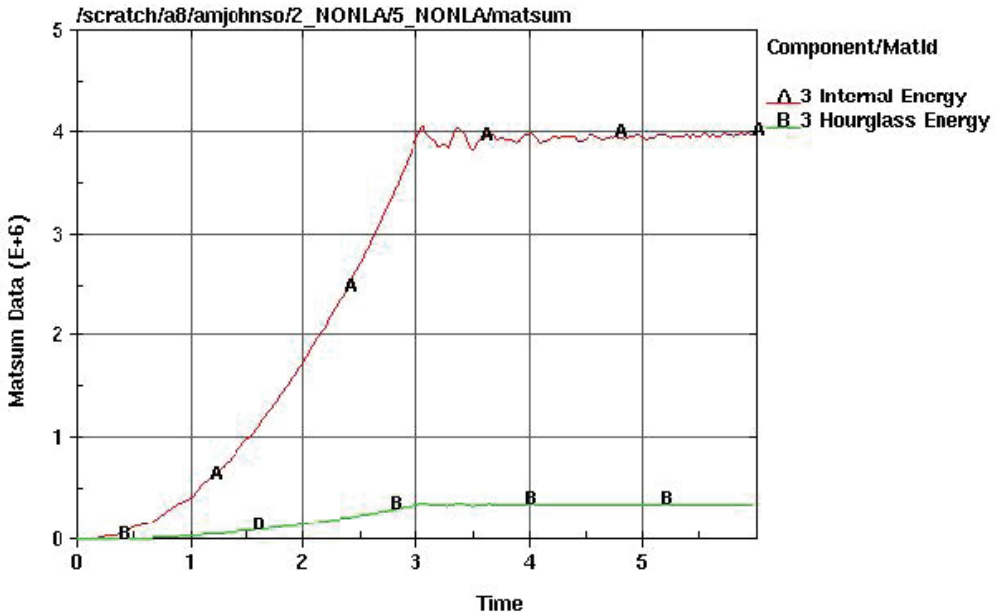


Figure 10e –Analysis 5, rock block internal and hourglass energies

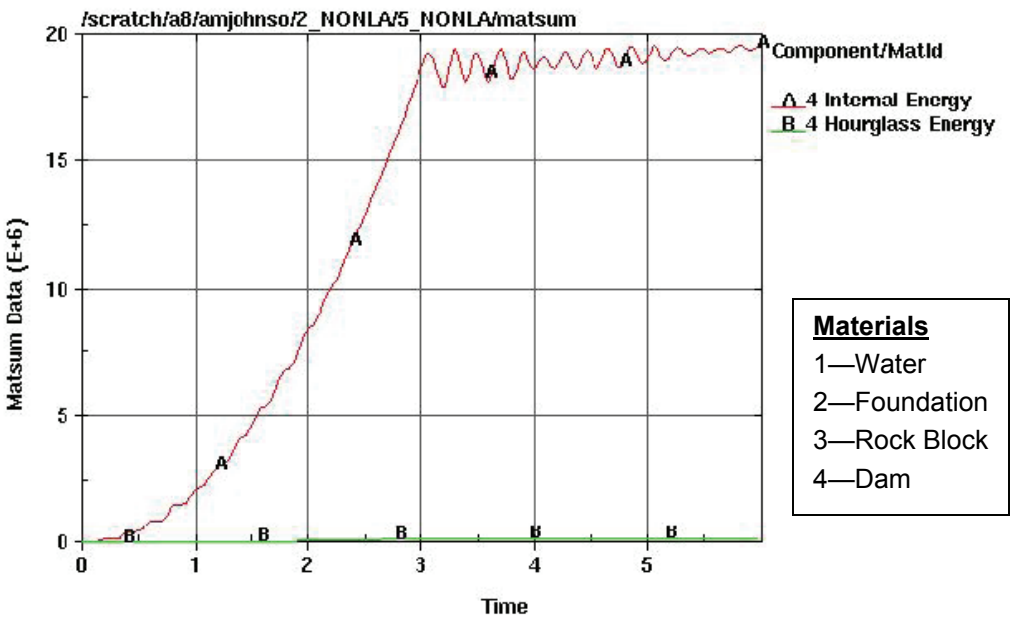


Figure 10f –Analysis 5, dam internal and hourglass energies

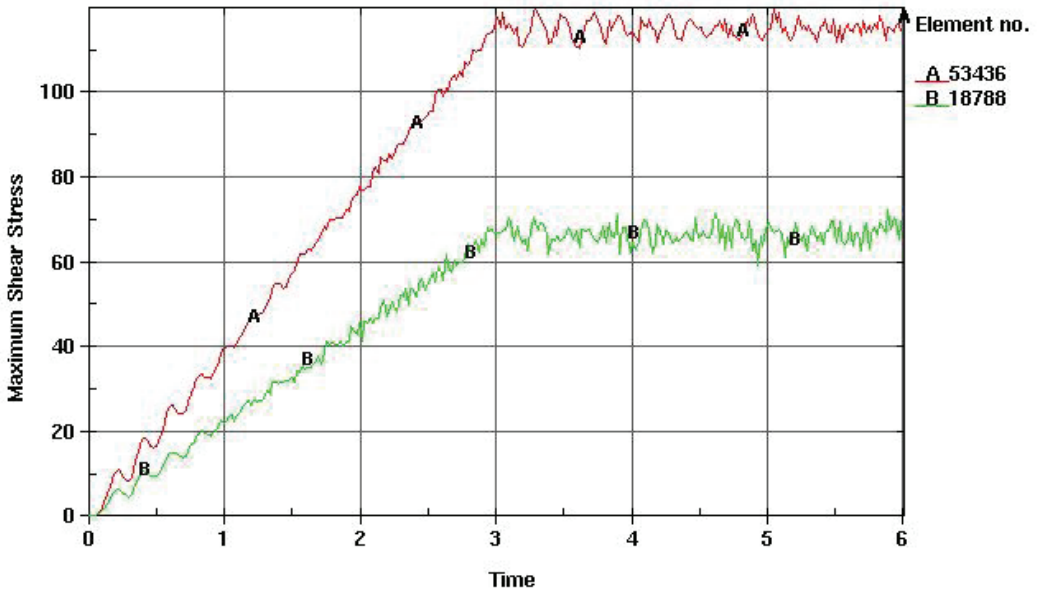


Figure 10g –Analysis 5, max shear stress at right foundation contact near rock block.

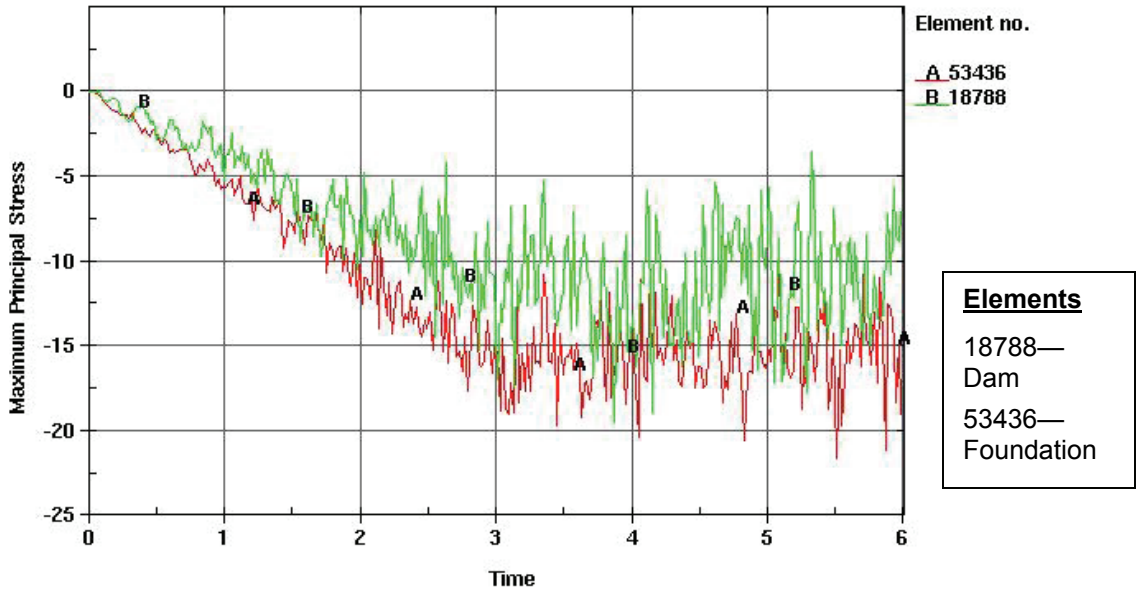


Figure 10h –Analysis 5, max principal stress at right foundation contact near rock block.

ANALYSIS 5.1
Analysis characteristics

IHQ (dam)	5
IHQ (foundation and rock block)	5
IHQ (water)	1
QM (dam)	0.10
QM (foundation and rock block)	0.10
QM (water)	0.0001
Foundation/dam mesh sizes	Fine/fine
Water/foundation contact	SURFACE_TO_SURFACE
…..notes	
Dam/water contact	SURFACE_TO_SURFACE
…..notes	
Foundation/dam contact	TIED_SURFACE_TO_SURFACE
…..notes	static and dynamic friction = 0.57
Rock block/foundation contact	AUTOMATIC_SURFACE_TO_SURFACE_TIEBREAK
…..notes	
Contraction joints	AUTOMATIC_SURFACE_TO_SURFACE_TIEBREAK
…..notes	static and dynamic friction = 0.57

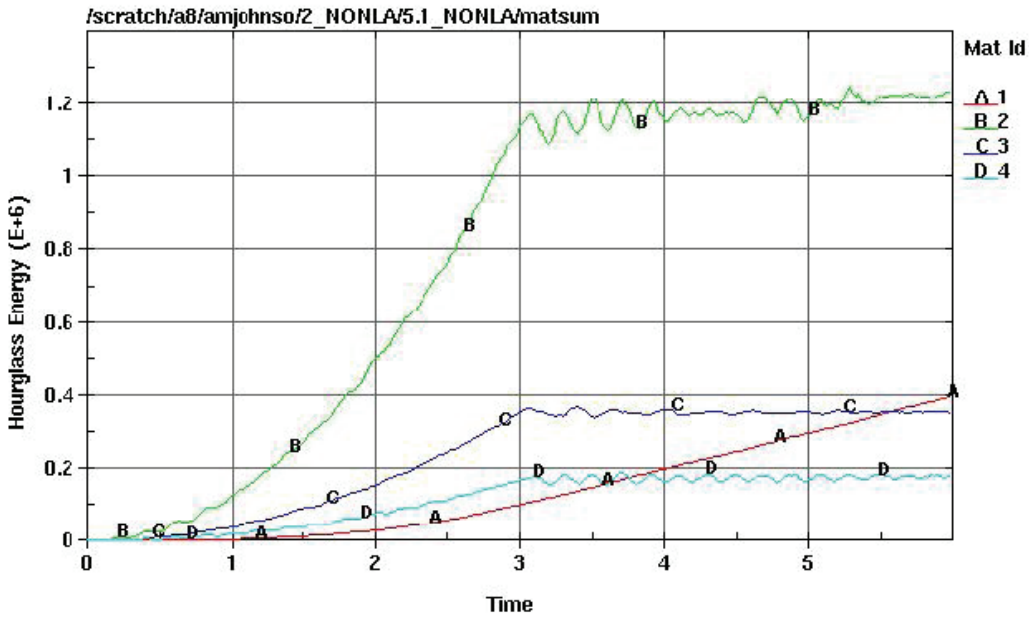


Figure 11a –Analysis 5.1 hourglass energy per material

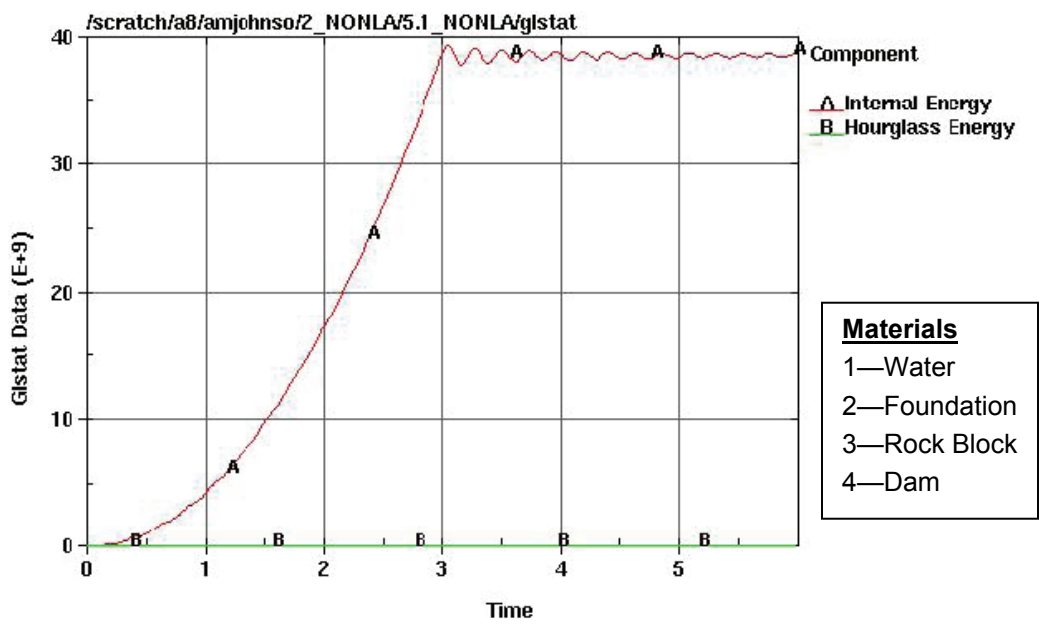


Figure 11b –Analysis 5.1 global internal and hourglass energies

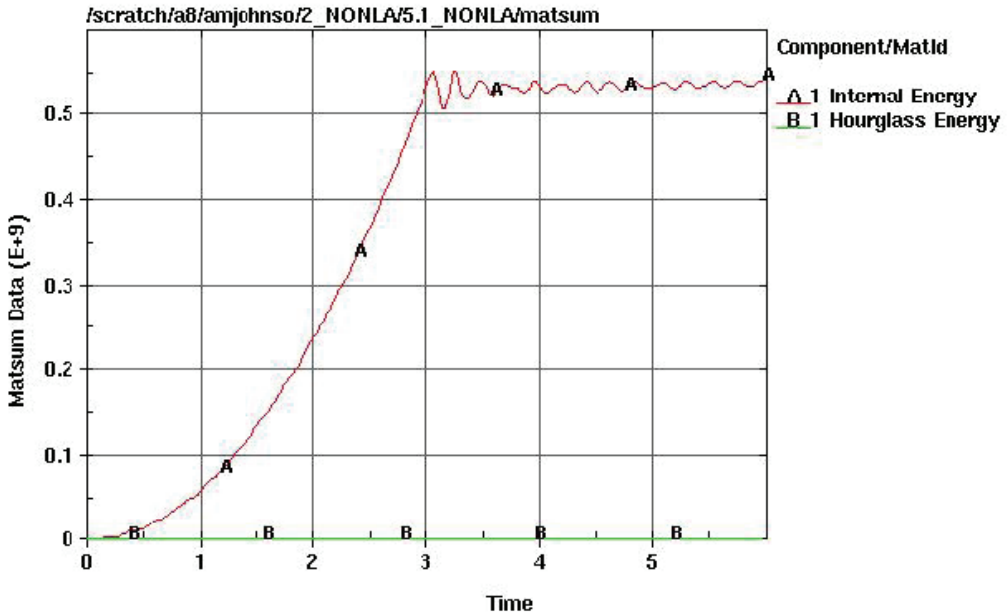


Figure 11c –Analysis 5.1, water, internal and hourglass energies

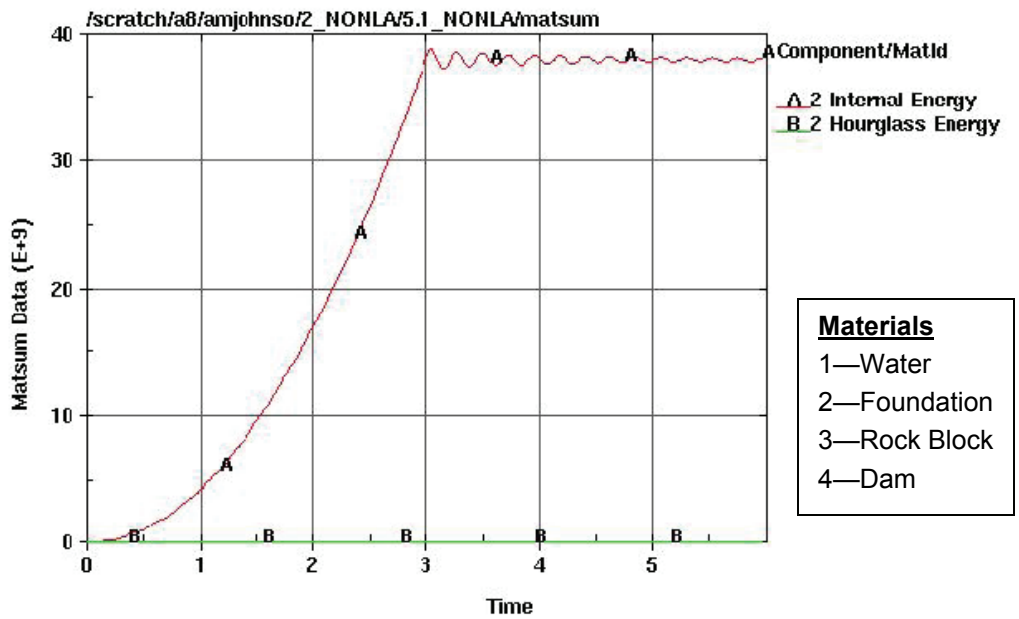


Figure 11d –Analysis 5.1, foundation, internal and hourglass energies

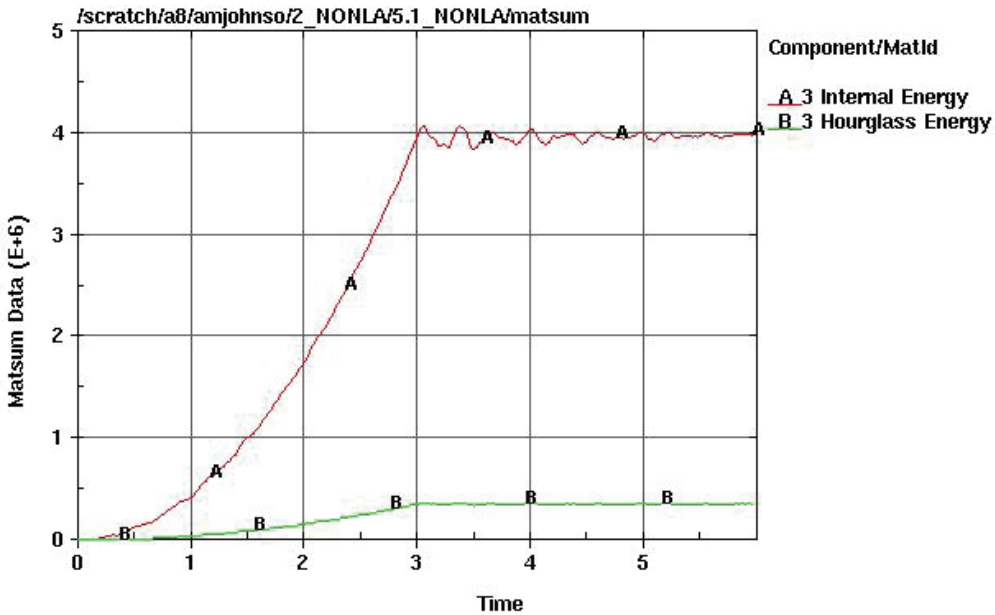


Figure 11e –Analysis 5.1, rock block internal and hourglass energies

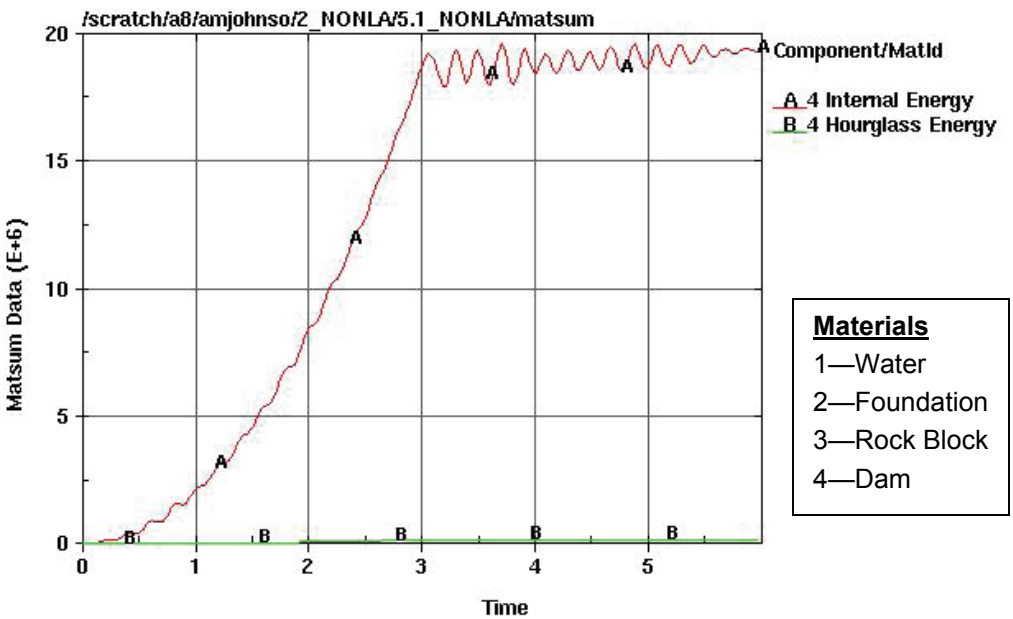


Figure 11f –Analysis 5.1, dam internal and hourglass energies

ANALYSIS 6
Analysis characteristics

IHQ (dam)	5
IHQ (foundation and rock block)	5
IHQ (water)	5
QM (dam)	0.10
QM (foundation and rock block)	0.10
QM (water)	0.10
Foundation/dam mesh sizes	Fine/coarse
Water/foundation contact	SURFACE_TO_SURFACE
…..notes	
Dam/water contact	SURFACE_TO_SURFACE
…..notes	
Foundation/dam contact	TIED_SURFACE_TO_SURFACE
…..notes	static and dynamic friction = 0.57
Rock block/foundation contact	AUTOMATIC_SURFACE_TO_SURFACE_TIEBREAK
…..notes	
Contraction joints	AUTOMATIC_SURFACE_TO_SURFACE_TIEBREAK
…..notes	static and dynamic friction = 0.57

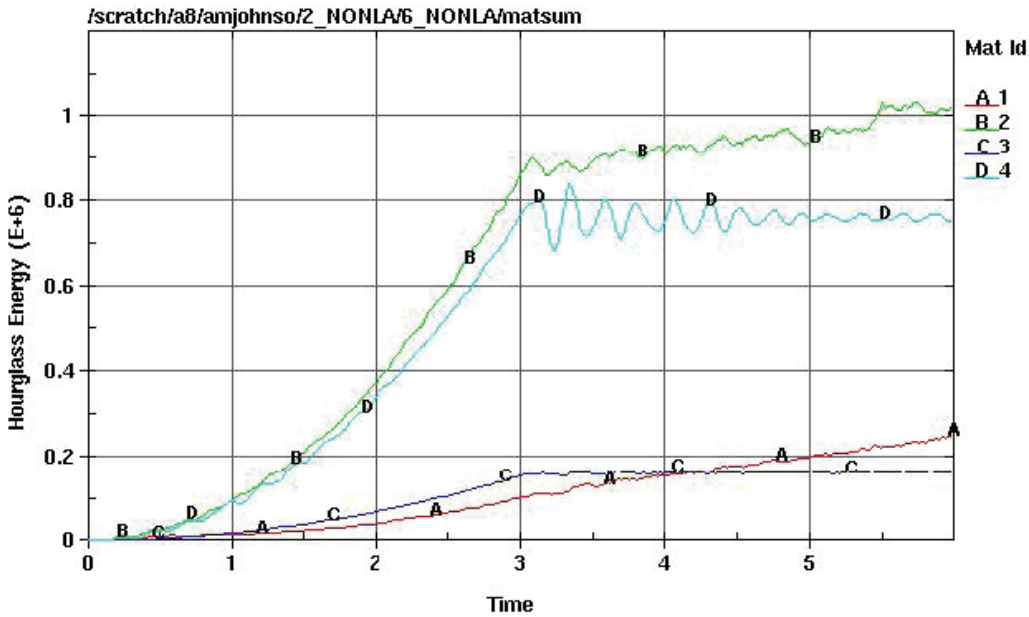


Figure 12a –Analysis 6 hourglass energy per material

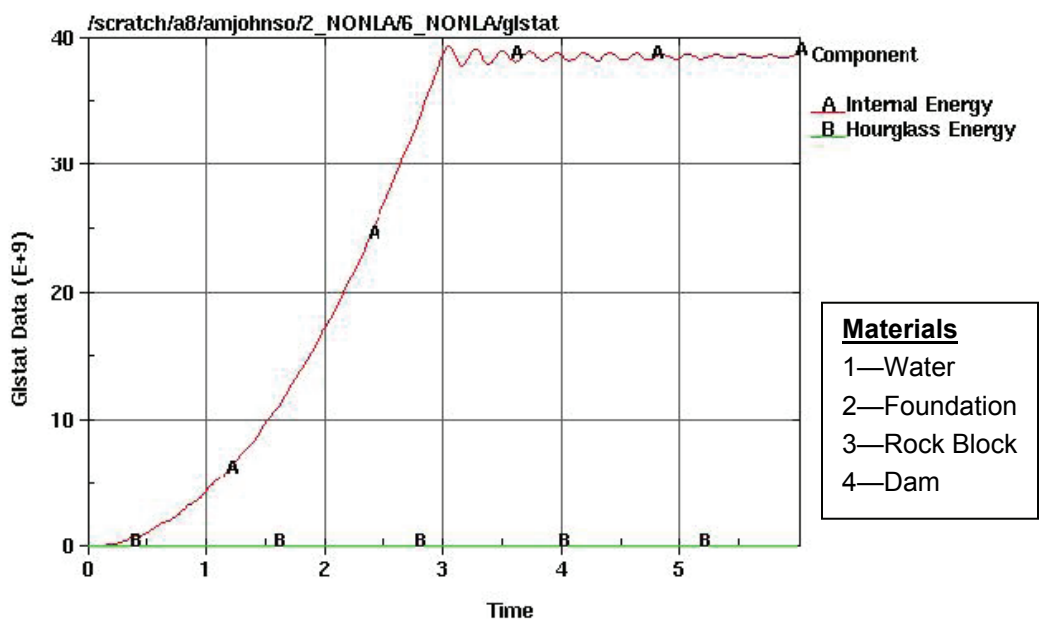


Figure 12b –Analysis 6 global internal and hourglass energies

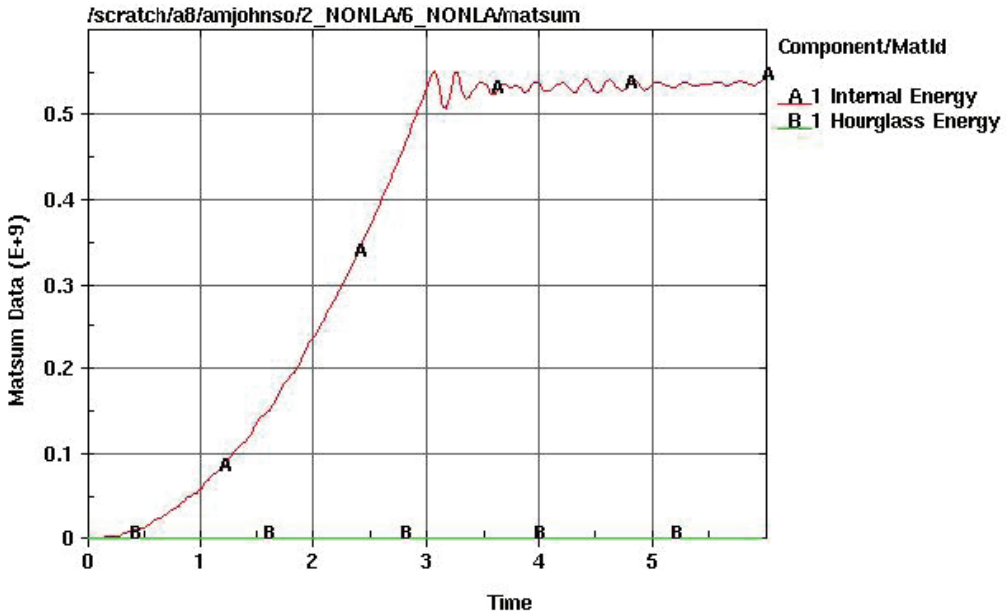


Figure 12c –Analysis 6, water, internal and hourglass energies

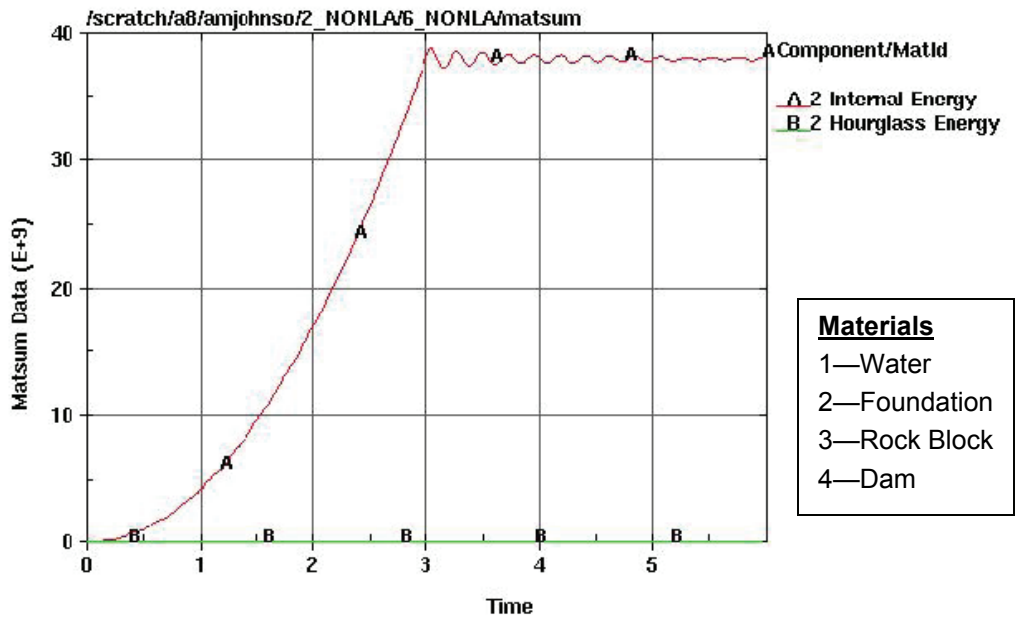


Figure 12d –Analysis 6, foundation, internal and hourglass energies

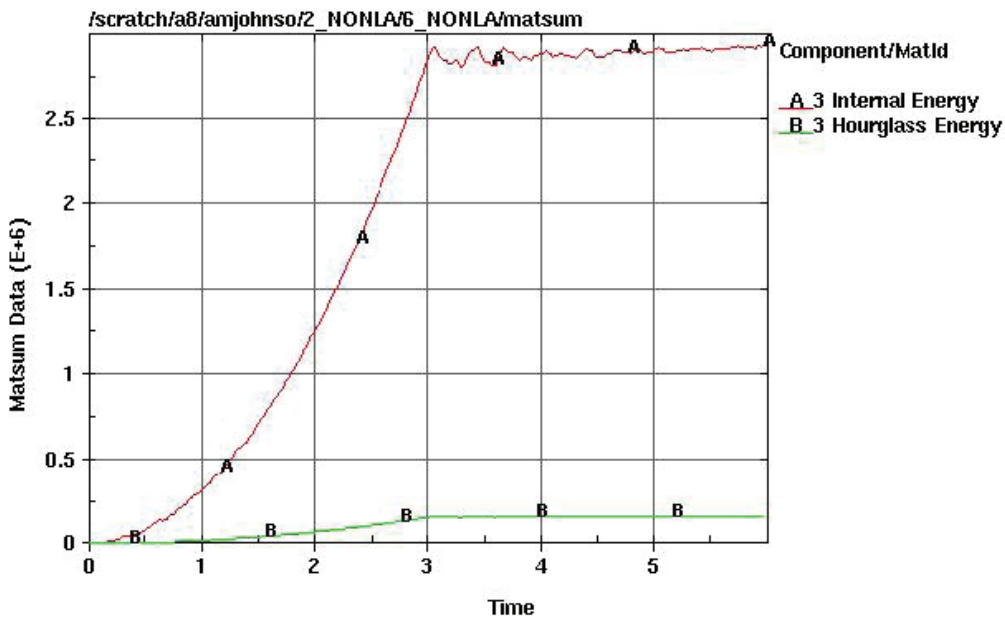


Figure 12e –Analysis 6, rock block internal and hourglass energies

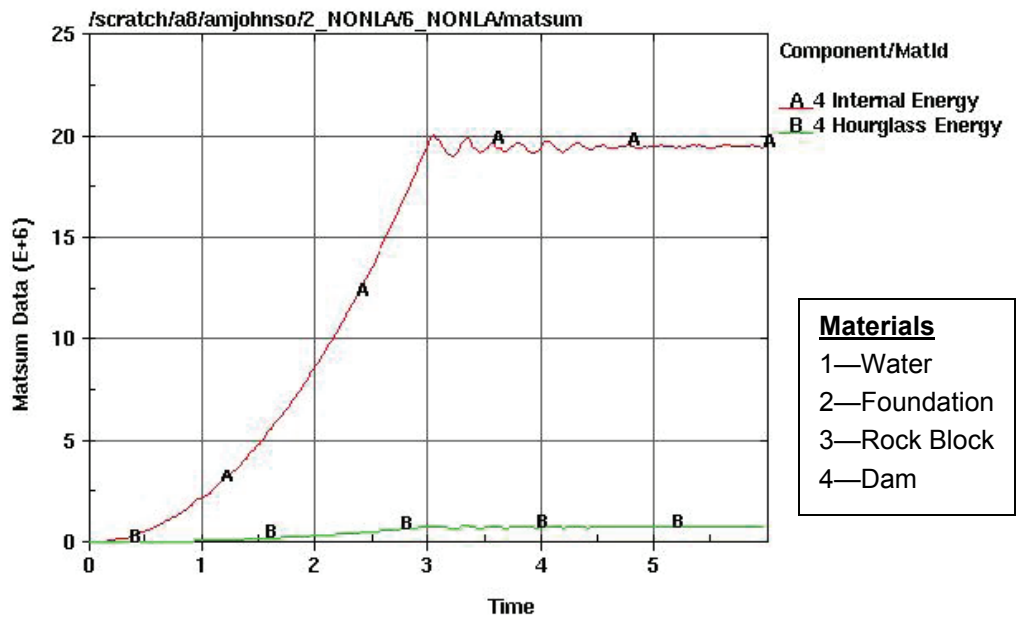


Figure 12f –Analysis 6, dam internal and hourglass energies

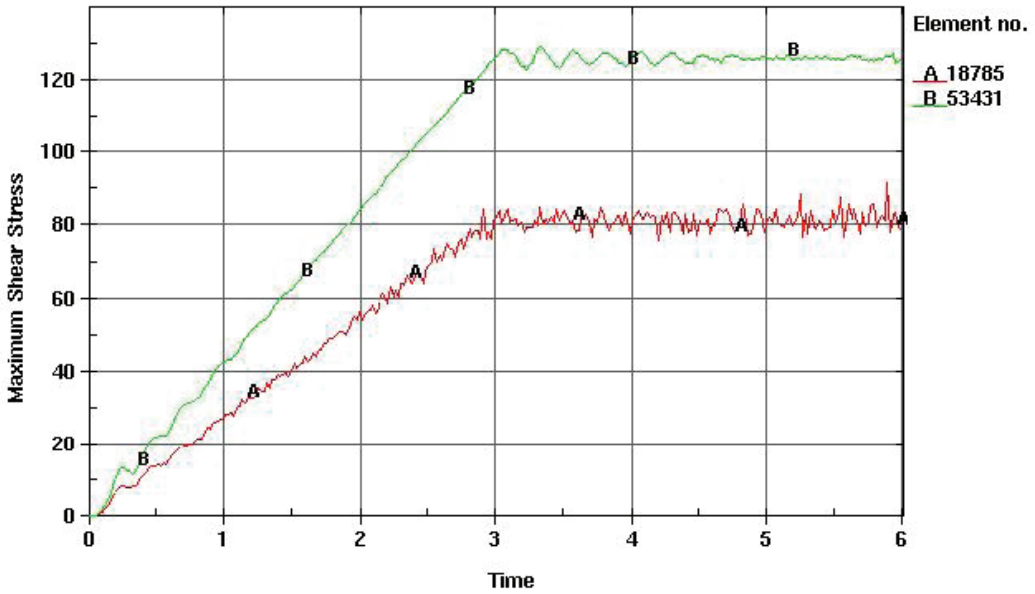


Figure 12g –Analysis 6, max shear stress at right foundation contact near rock block.

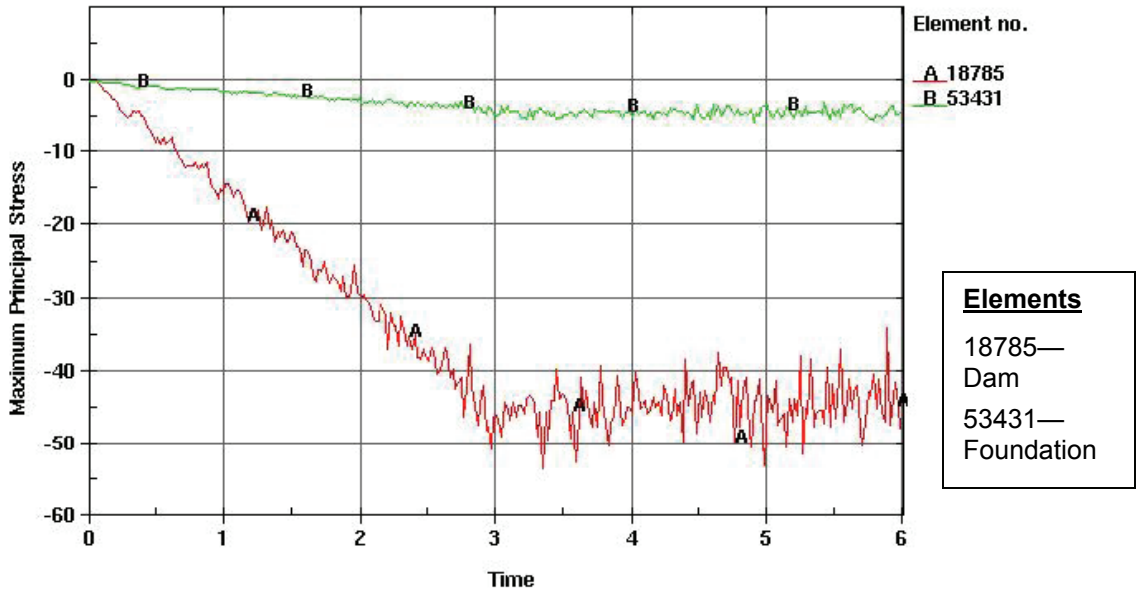


Figure 12h –Analysis 6, max principal stress at right foundation contact near rock block.

ANALYSIS 5.1
Analysis characteristics

IHQ (dam)	5
IHQ (foundation and rock block)	5
IHQ (water)	5
QM (dam)	0.10
QM (foundation and rock block)	0.10
QM (water)	0.01
Foundation/dam mesh sizes	Fine/fine
Water/foundation contact	SURFACE_TO_SURFACE
…..notes	
Dam/water contact	SURFACE_TO_SURFACE
…..notes	
Foundation/dam contact	TIED_SURFACE_TO_SURFACE
…..notes	static and dynamic friction = 0.57
Rock block/foundation contact	AUTOMATIC_SURFACE_TO_SURFACE_TIEBREAK
…..notes	
Contraction joints	AUTOMATIC_SURFACE_TO_SURFACE_TIEBREAK
…..notes	static and dynamic friction = 0.57

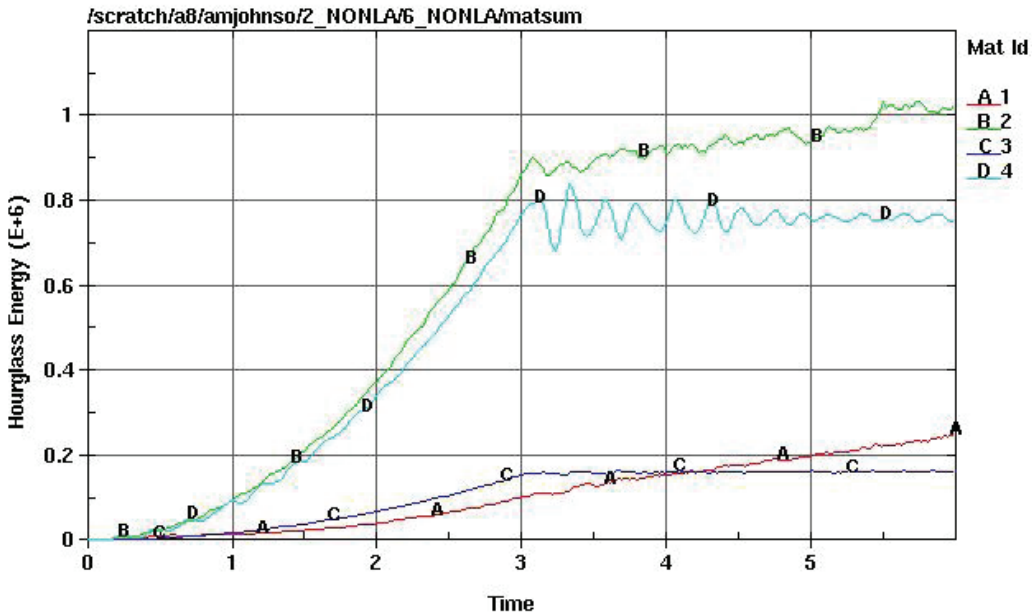


Figure 13a –Analysis 6.1 hourglass energy per material

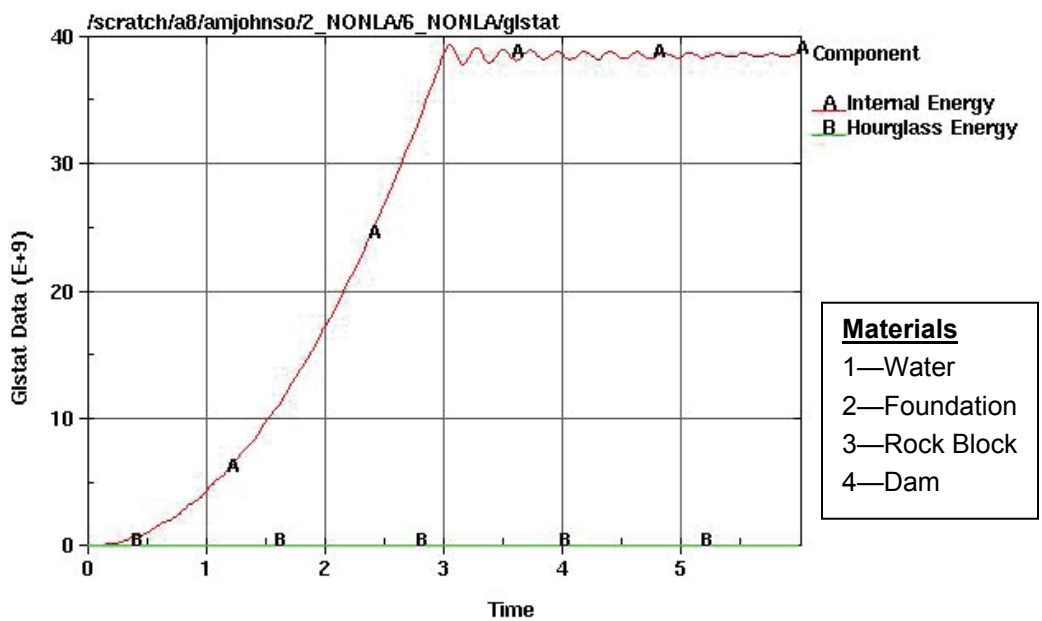


Figure 13b –Analysis 6.1 global internal and hourglass energies

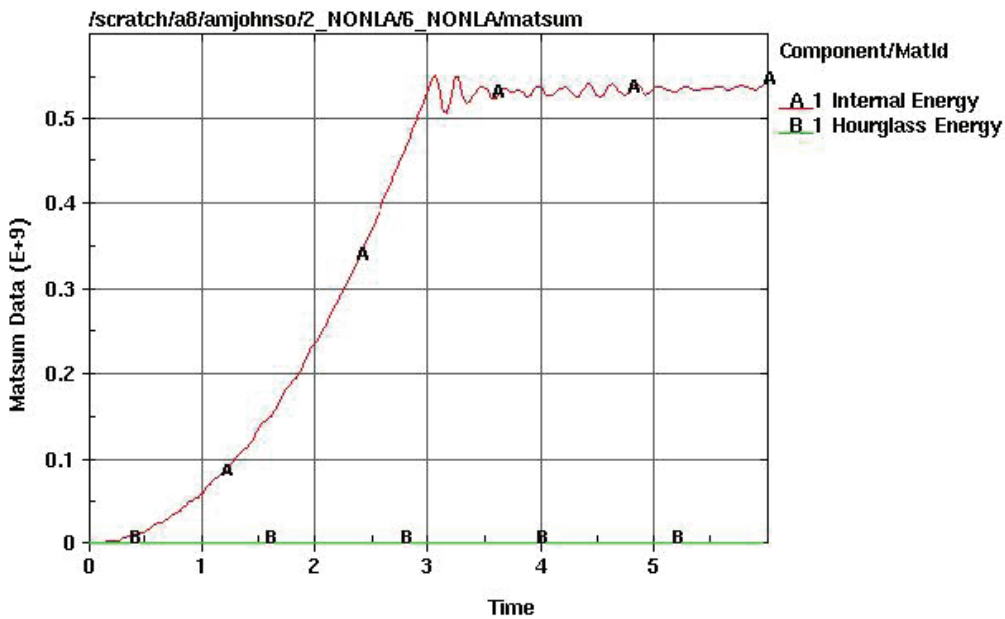


Figure 13c –Analysis 6.1, water, internal and hourglass energies

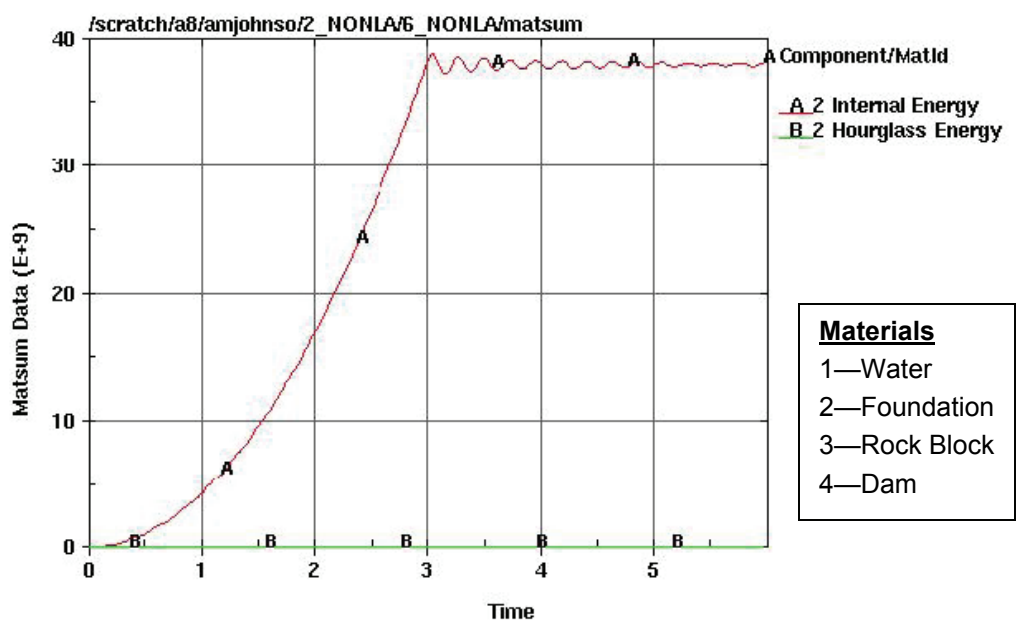


Figure 13d –Analysis 6.1, foundation, internal and hourglass energies

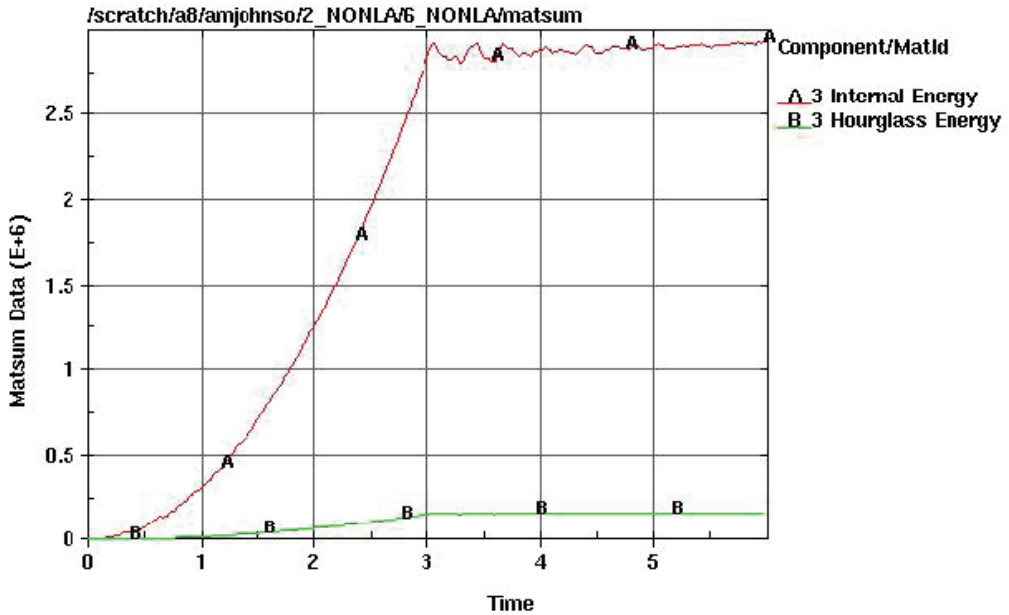


Figure 13e –Analysis 6.1, rock block internal and hourglass energies

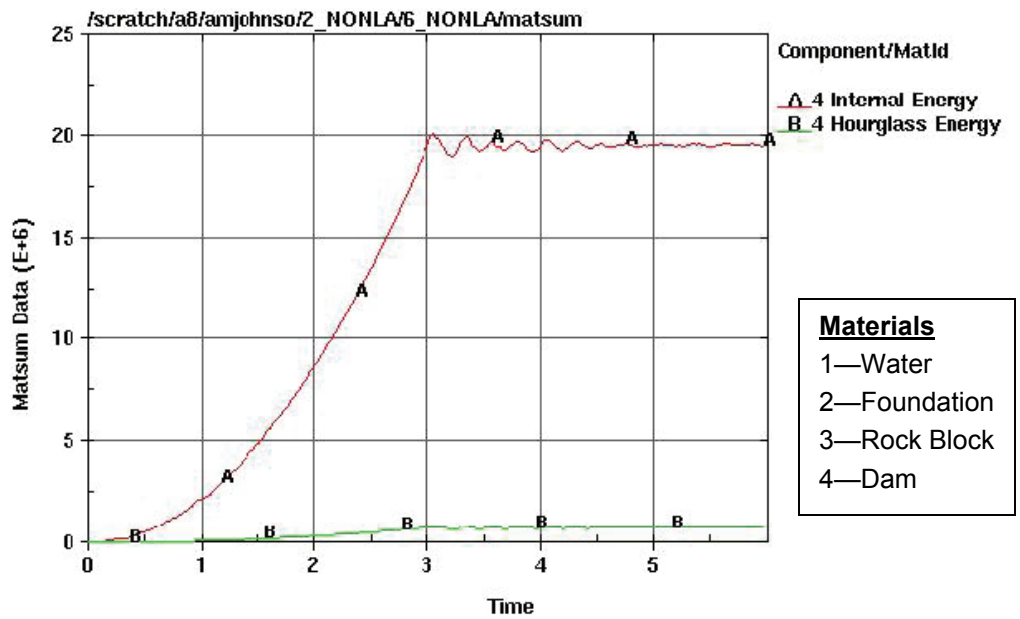


Figure 13f –Analysis 6.1, dam internal and hourglass energies

Appendix B—Traction Load Study—Input and Target Motions

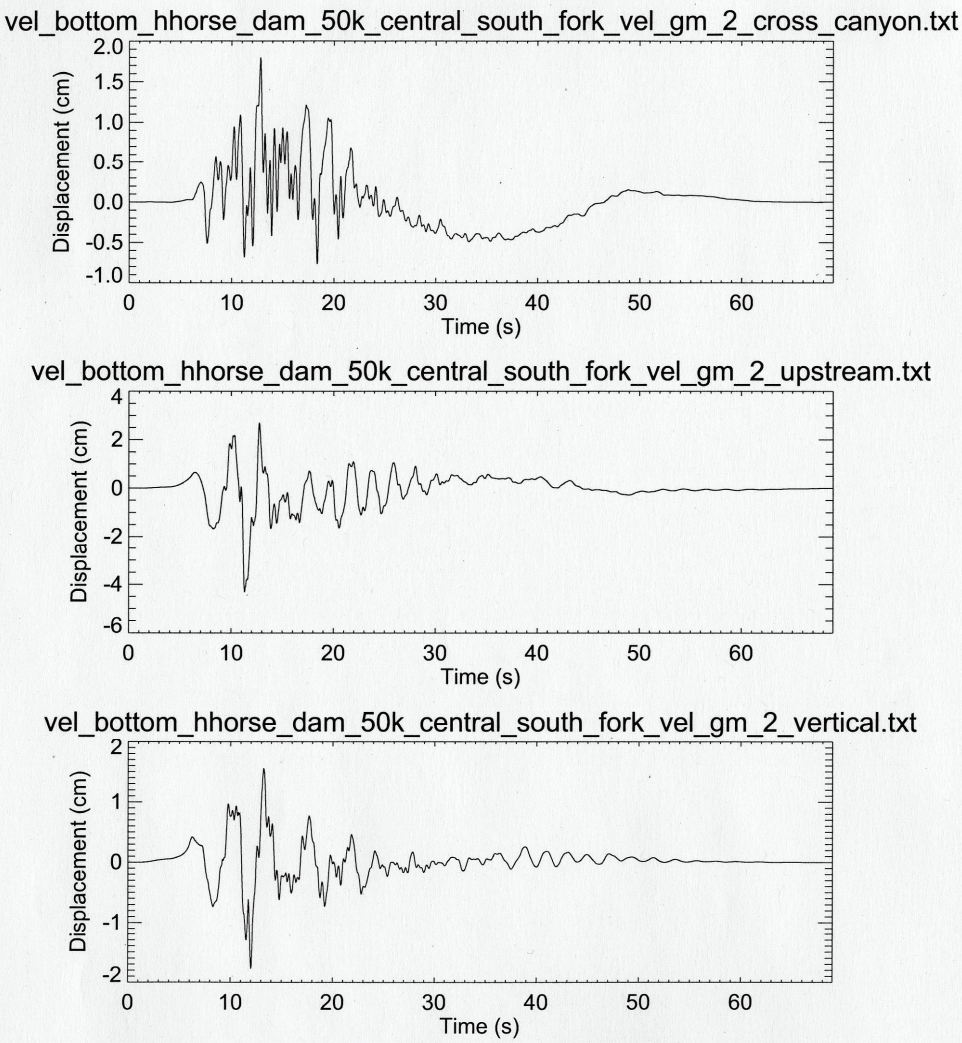


Figure B-1 – Displacement Time Histories – Input Motions (Deconvolved Motions)

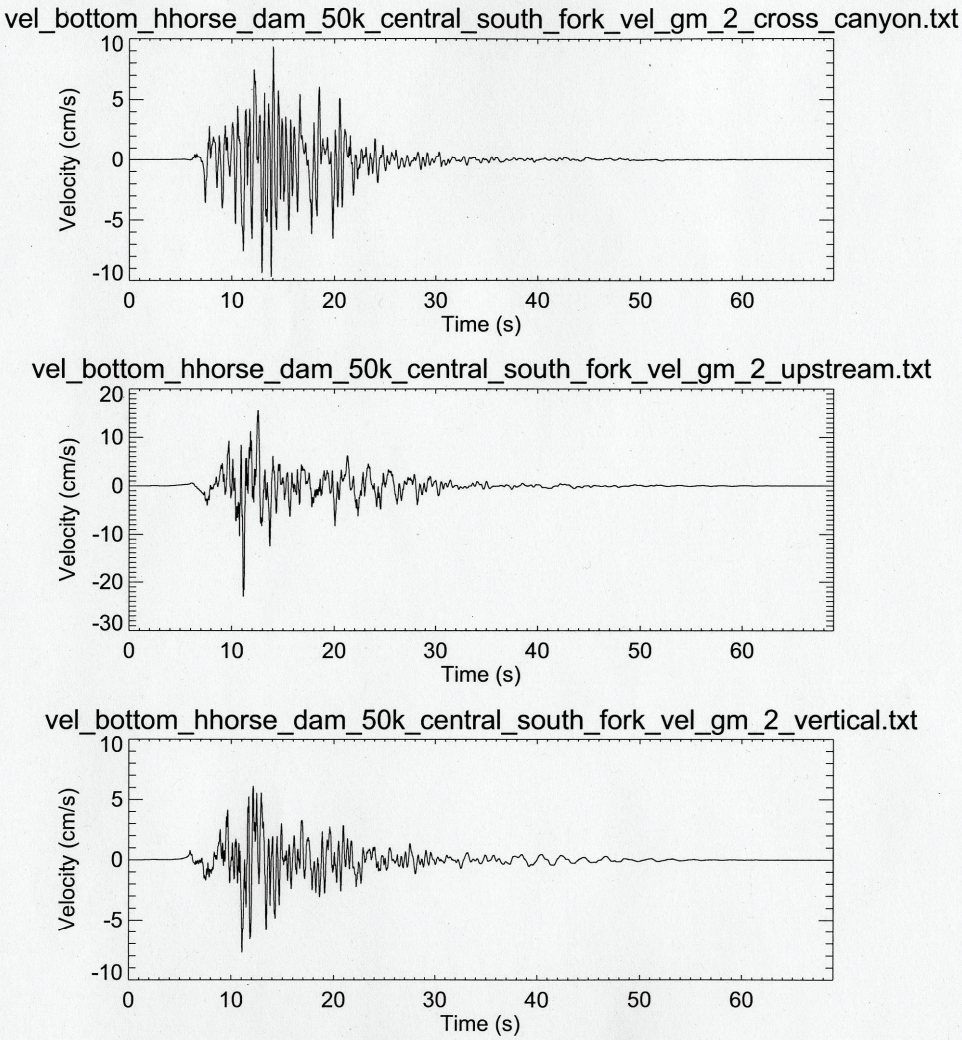


Figure B-2 – Velocity Time Histories - Velocities Used for Input Motions (Deconvolved Motions)

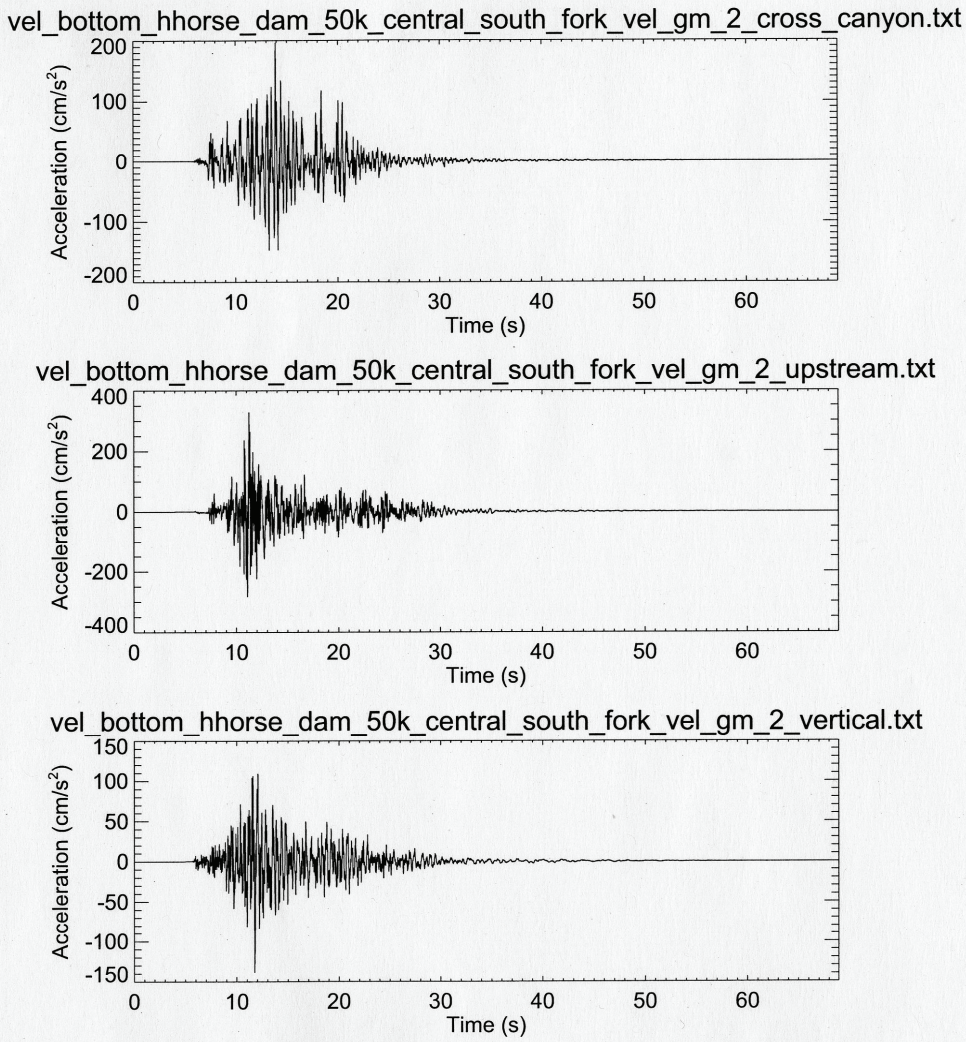


Figure B-3 – Acceleration Time Histories – Input Motions (Deconvolved Motions)

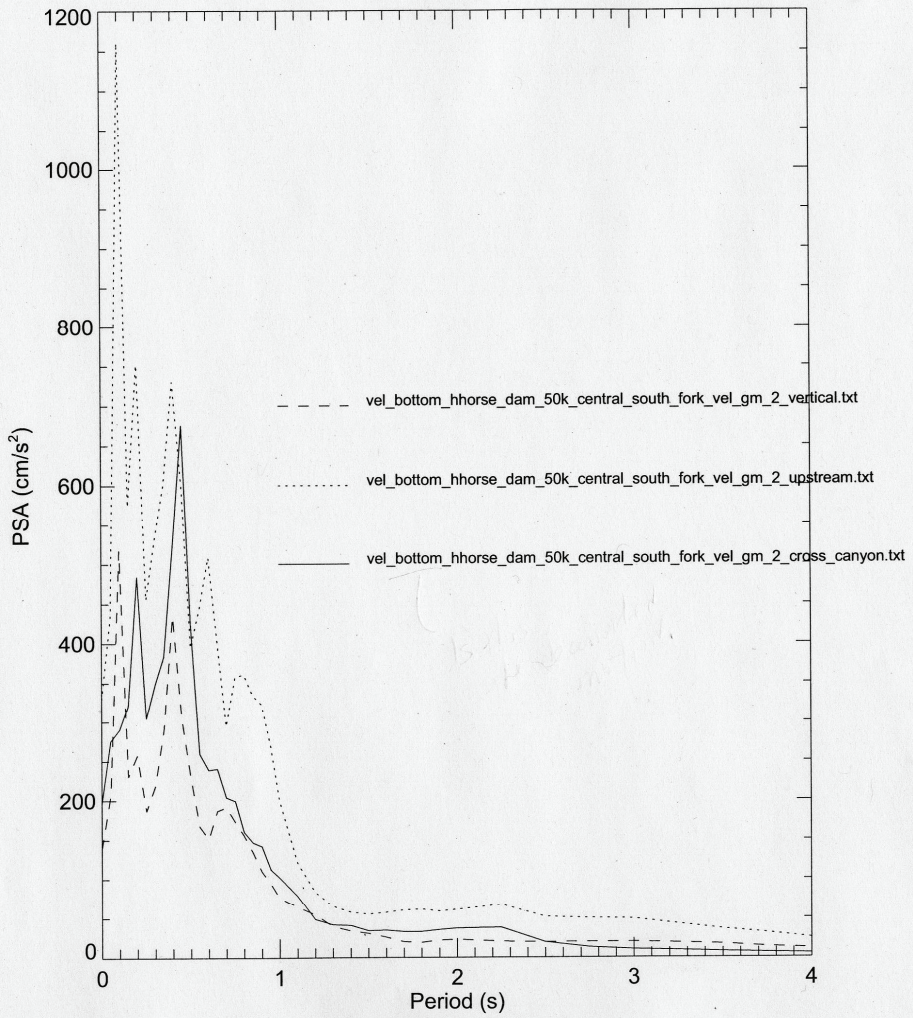


Figure B-4 – Acceleration Response Spectra – Input Motions (Deconvolved Motions)

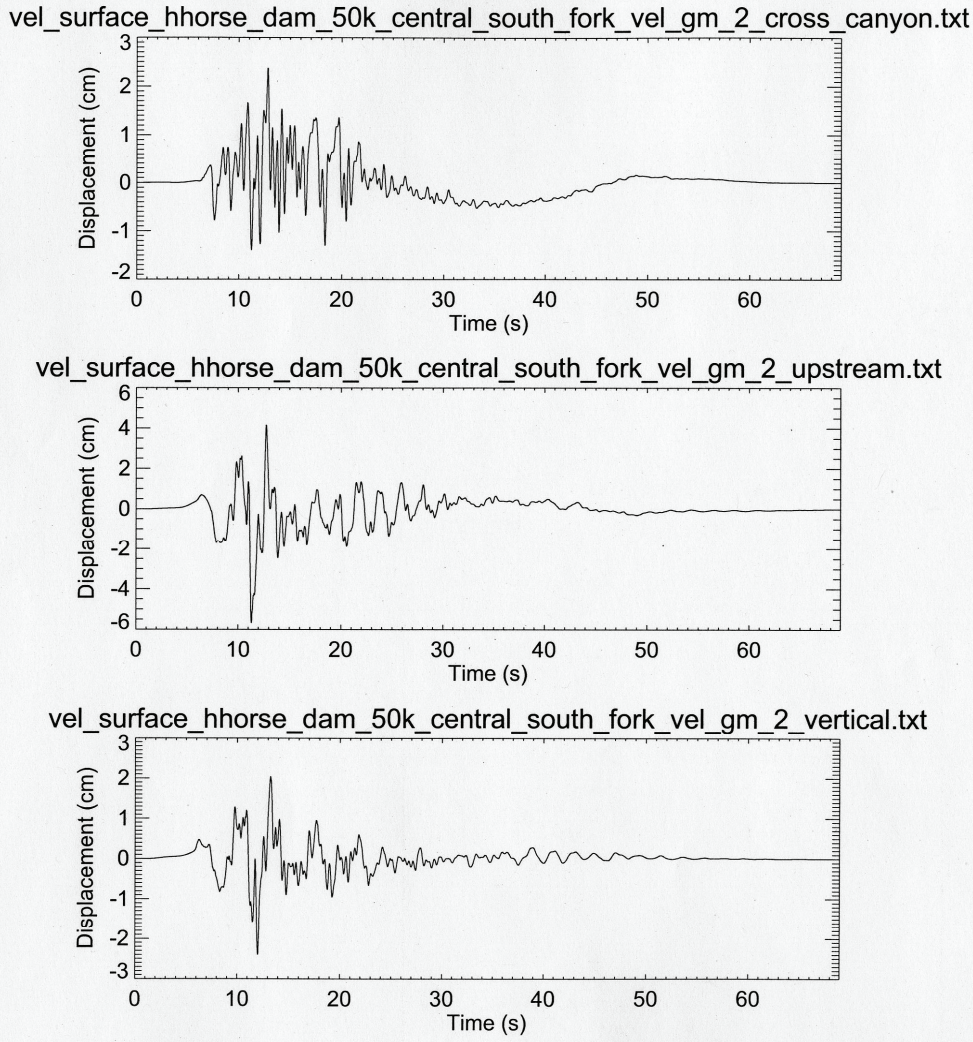


Figure B-5 Displacement Time Histories – Target Motions

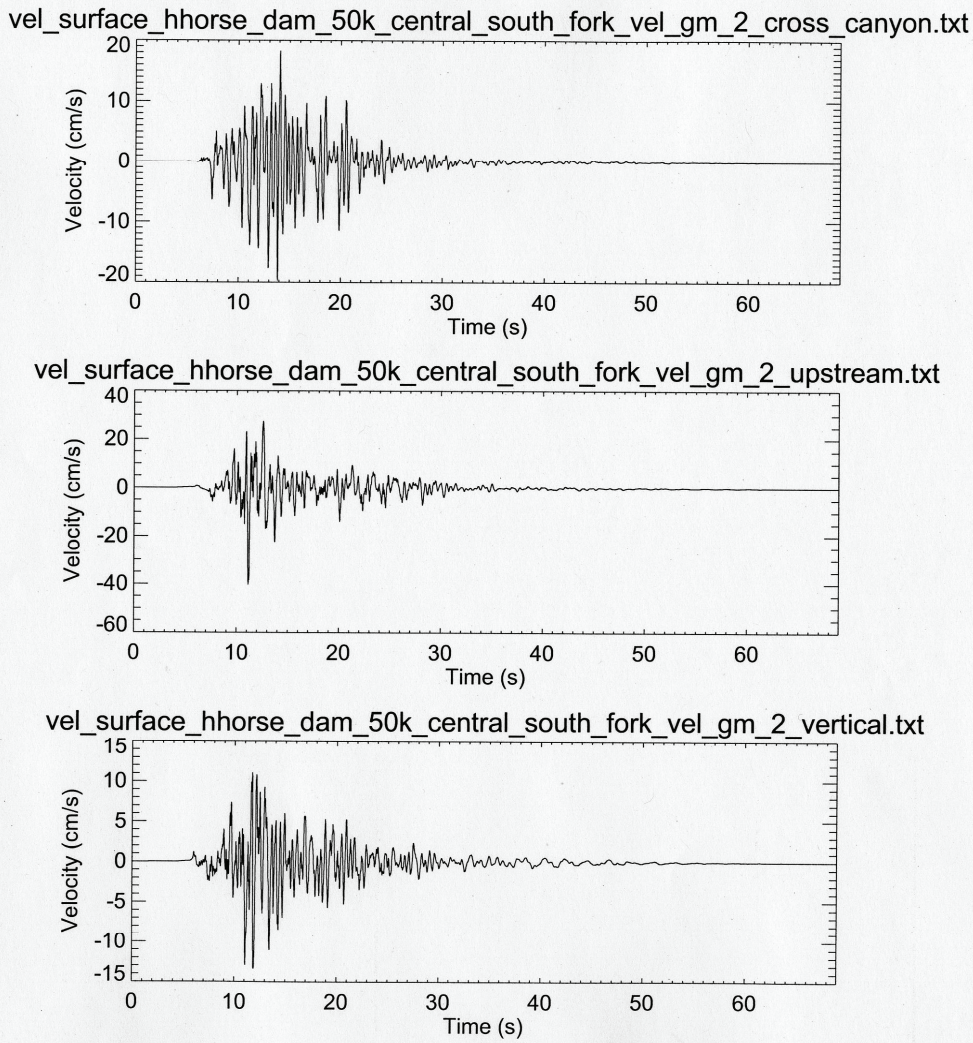


Figure B-6 Velocity Time Histories – Target Motions

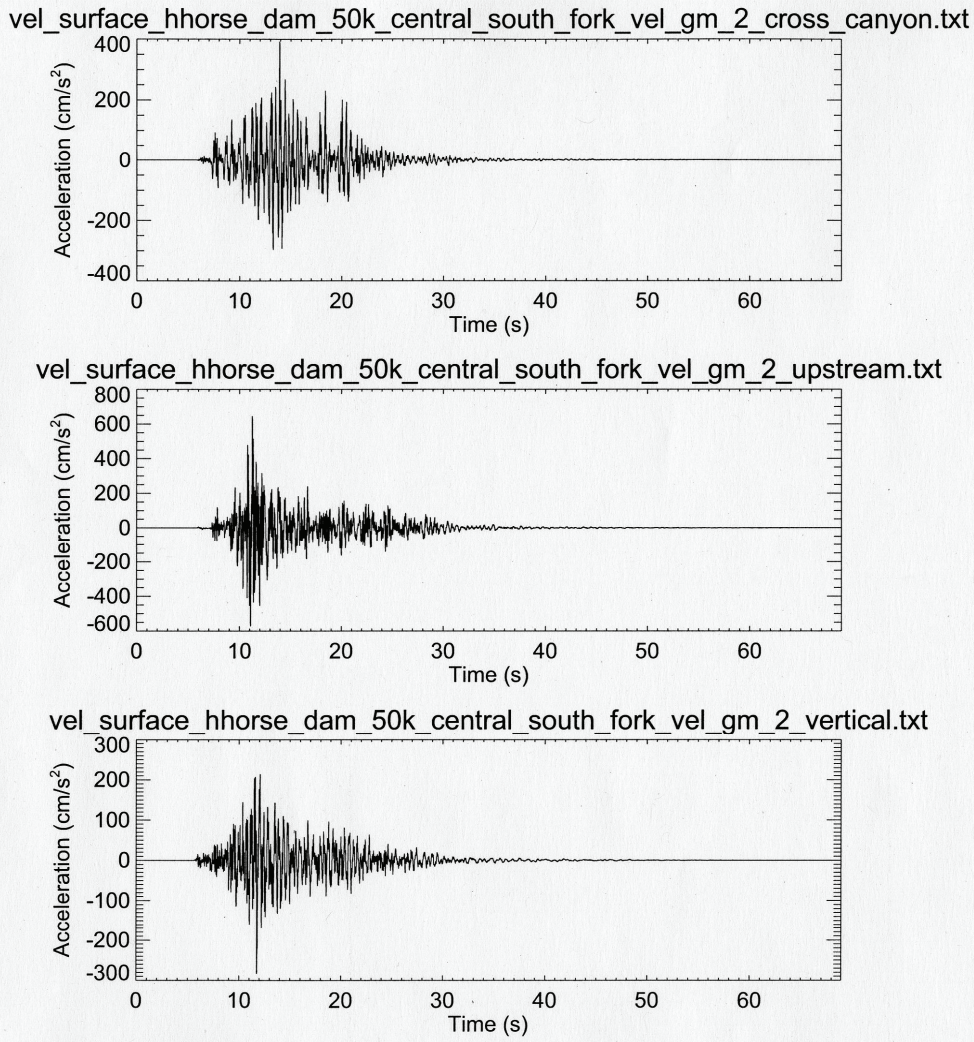


Figure B-7 Acceleration Time Histories – Target Motions

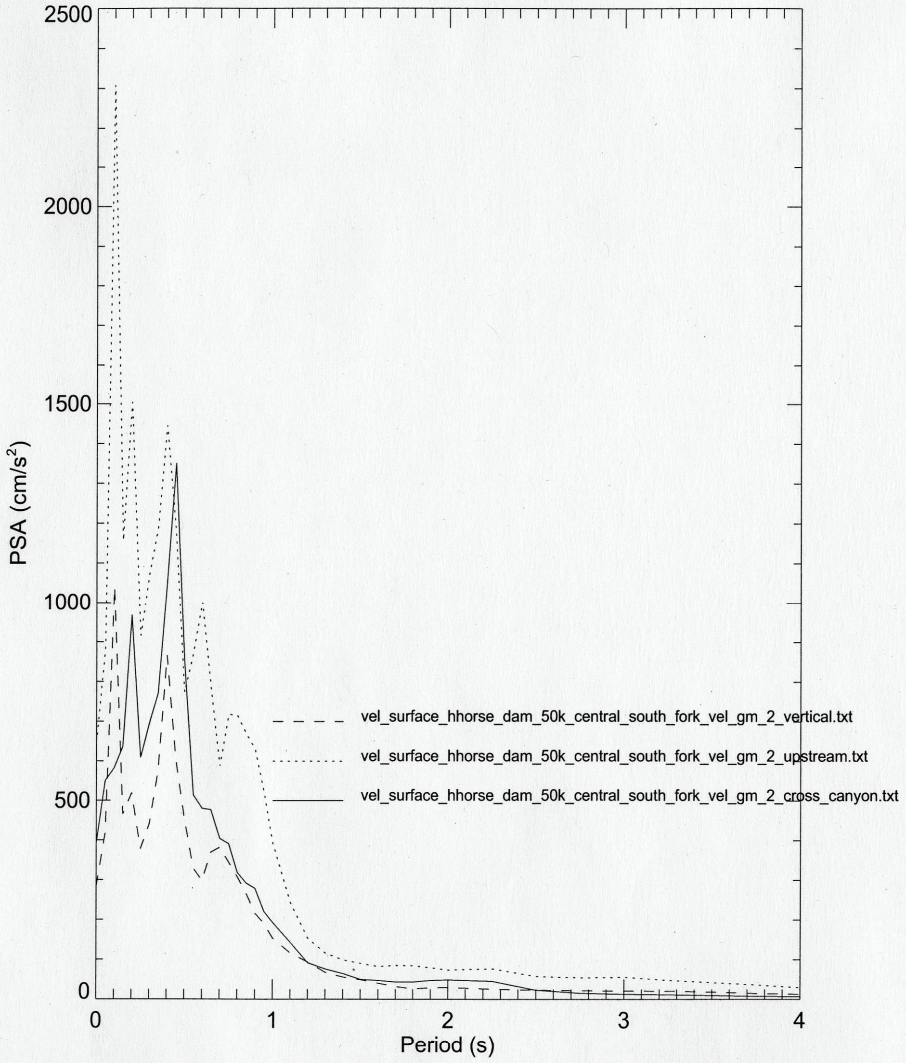
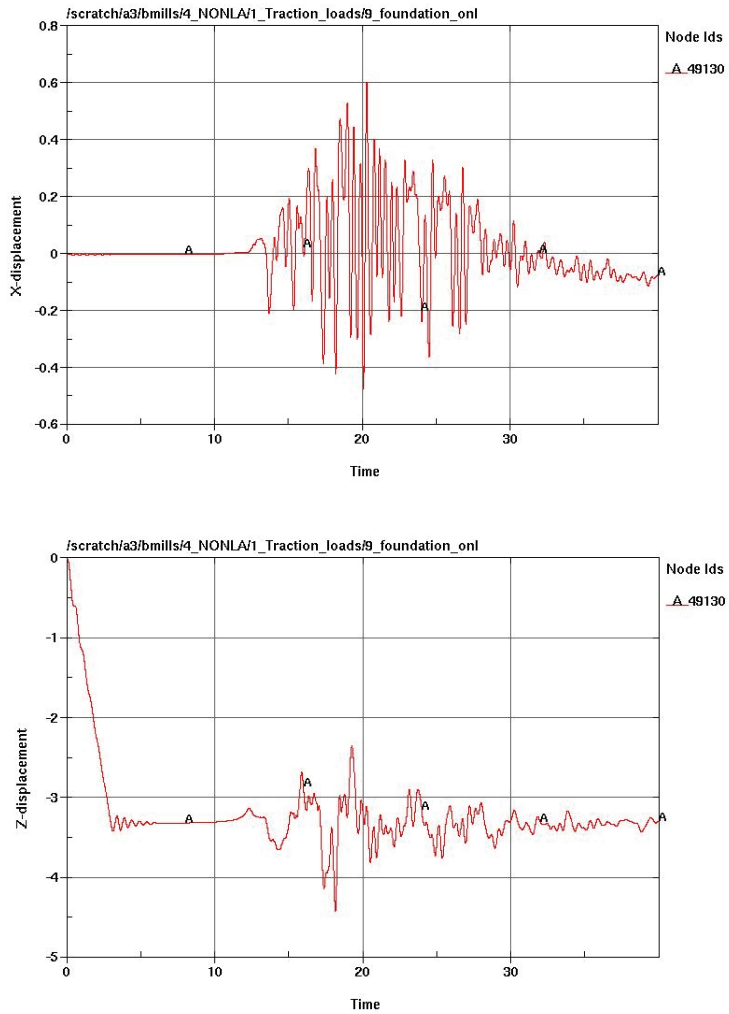


Figure B-8 Acceleration Response Spectra – Target Motions

Appendix C—Time History Plots of Displacement, Velocity, and Acceleration



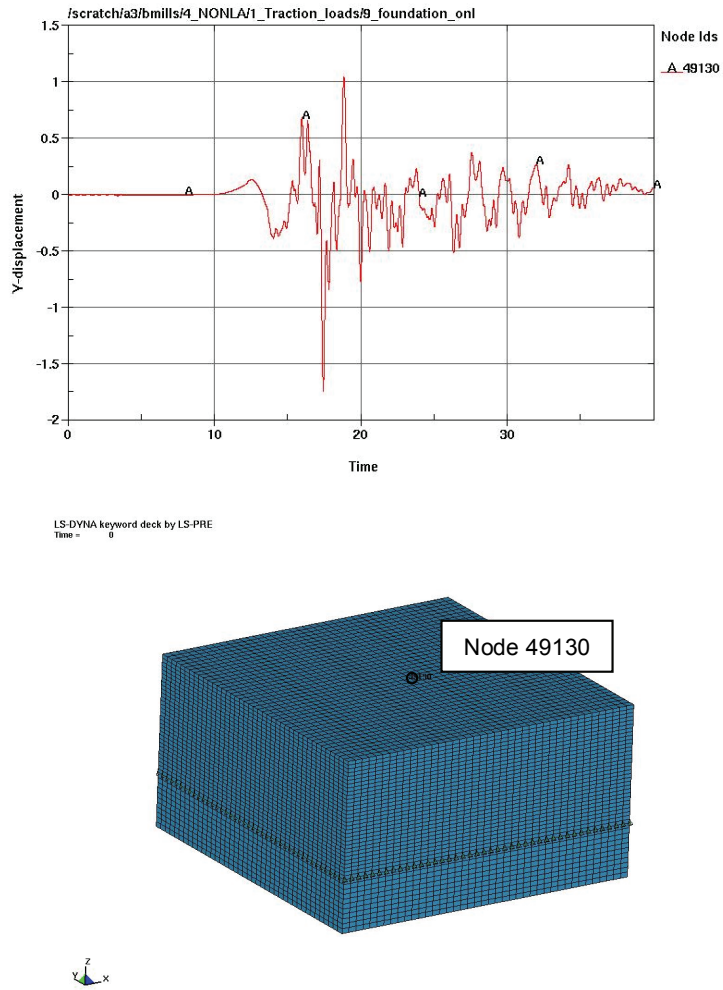
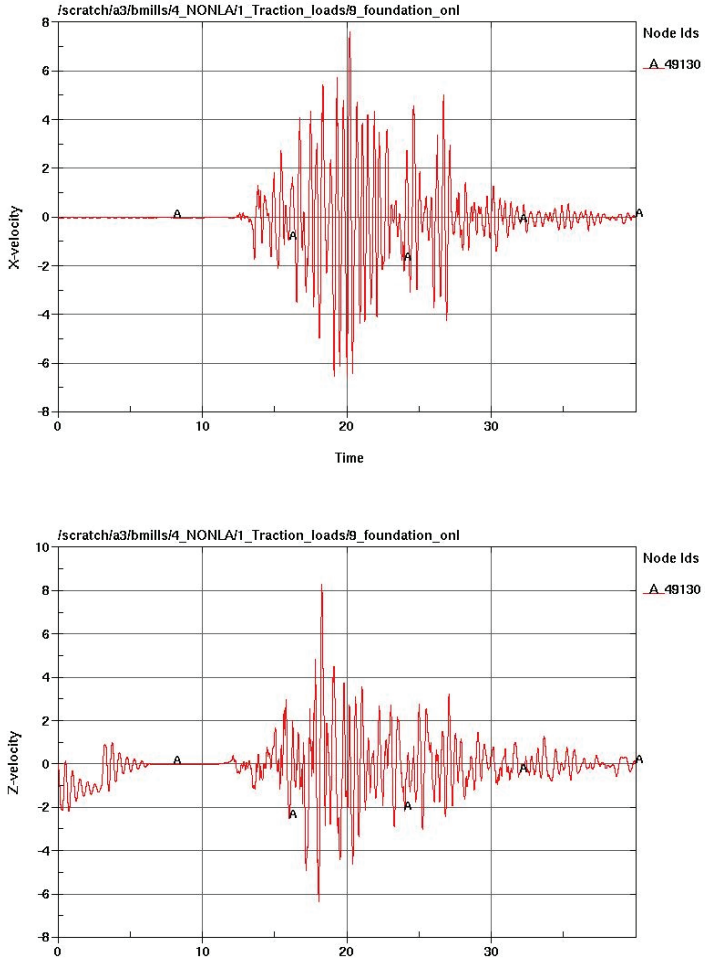


Figure C-1—Applied traction loads—displacements.



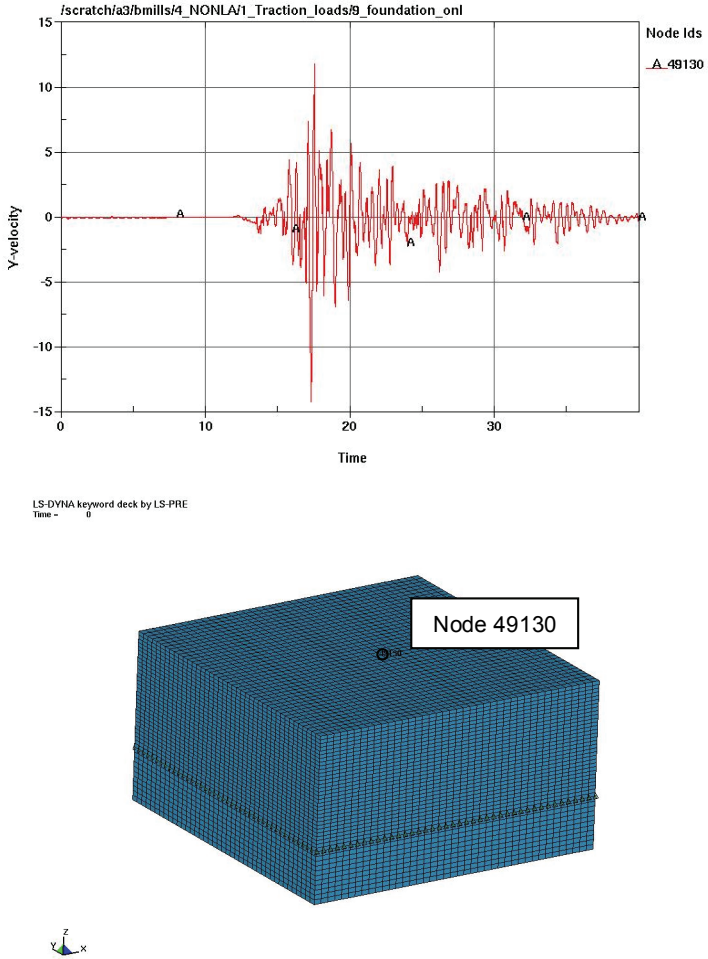
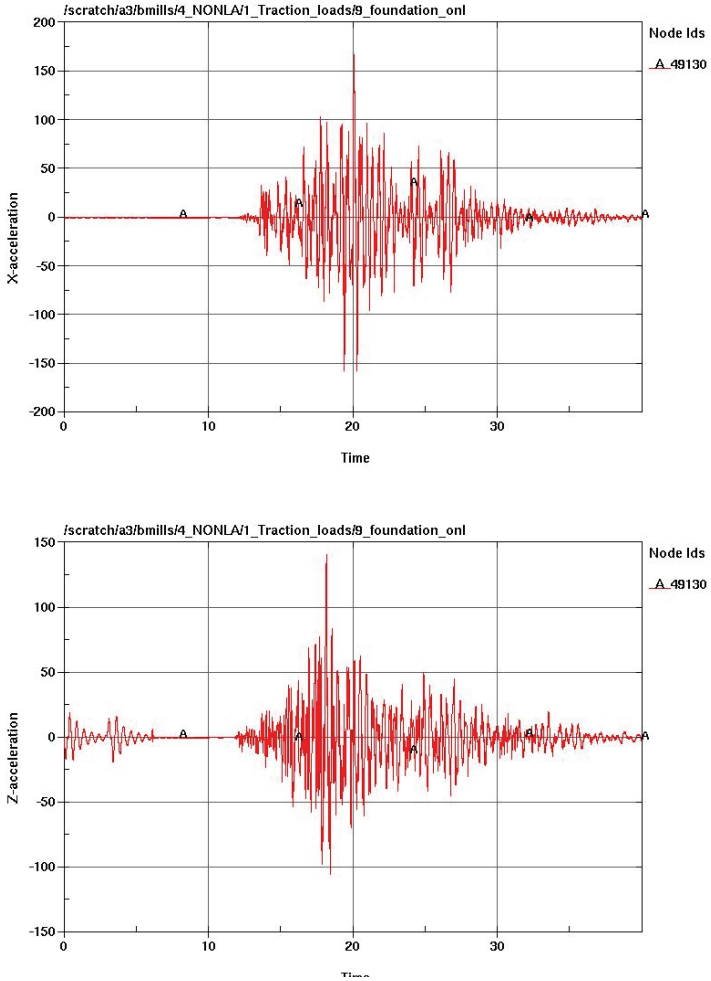


Figure C-2—Applied traction loads—velocities.



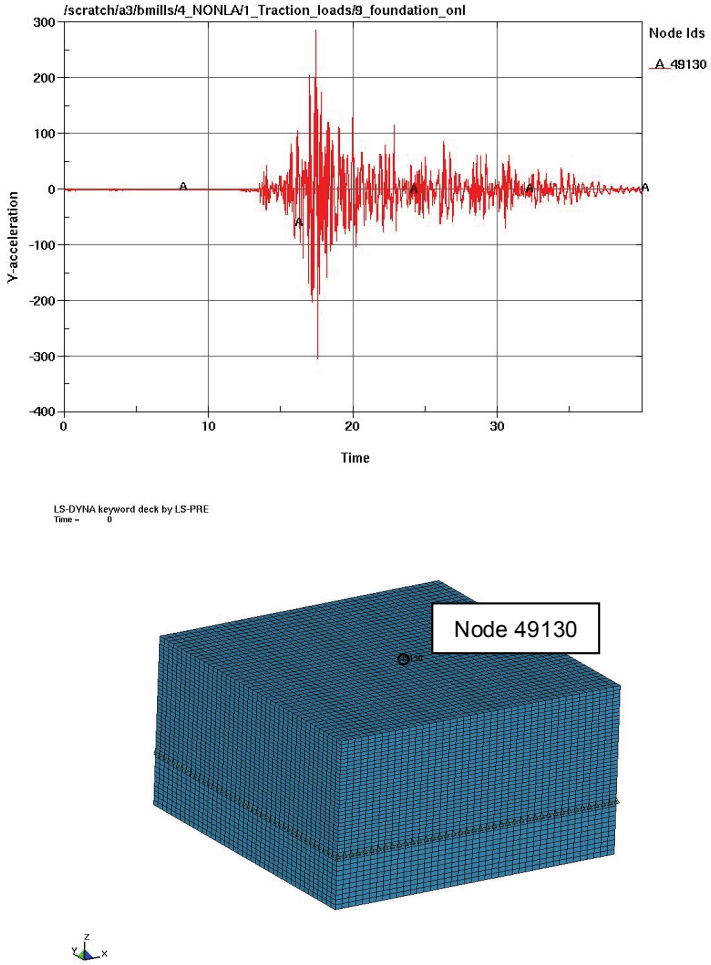
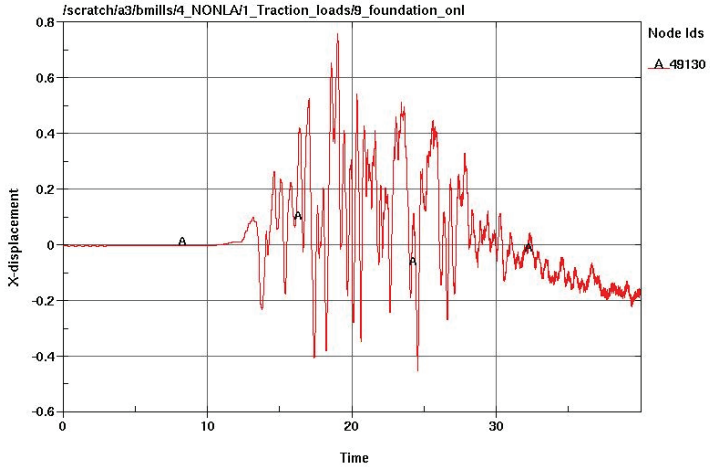
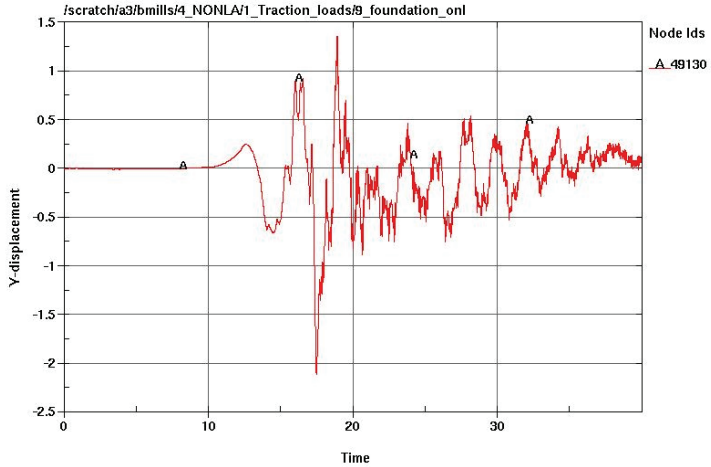
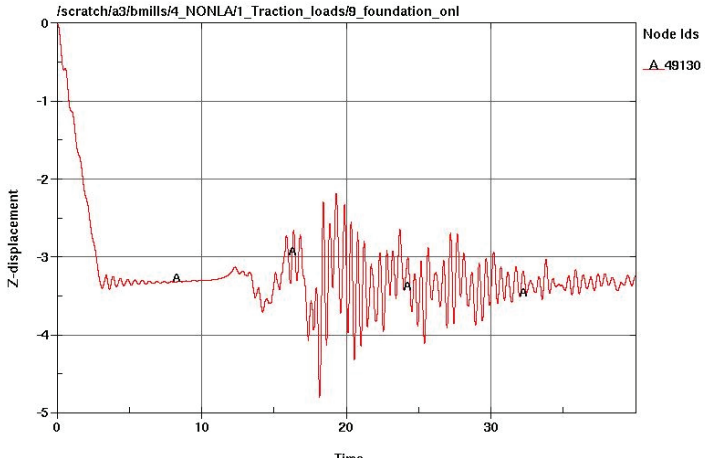


Figure C-3—Applied traction loads—accelerations.







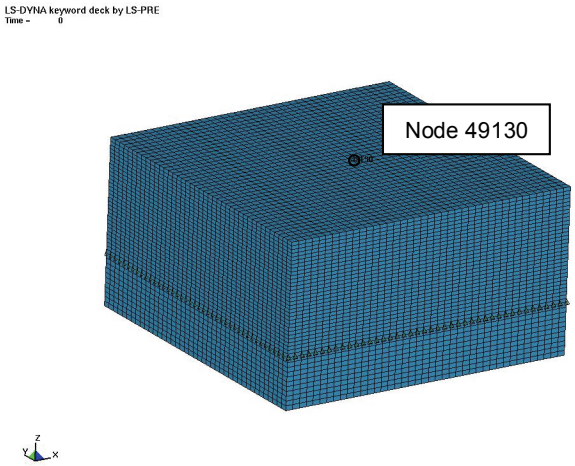
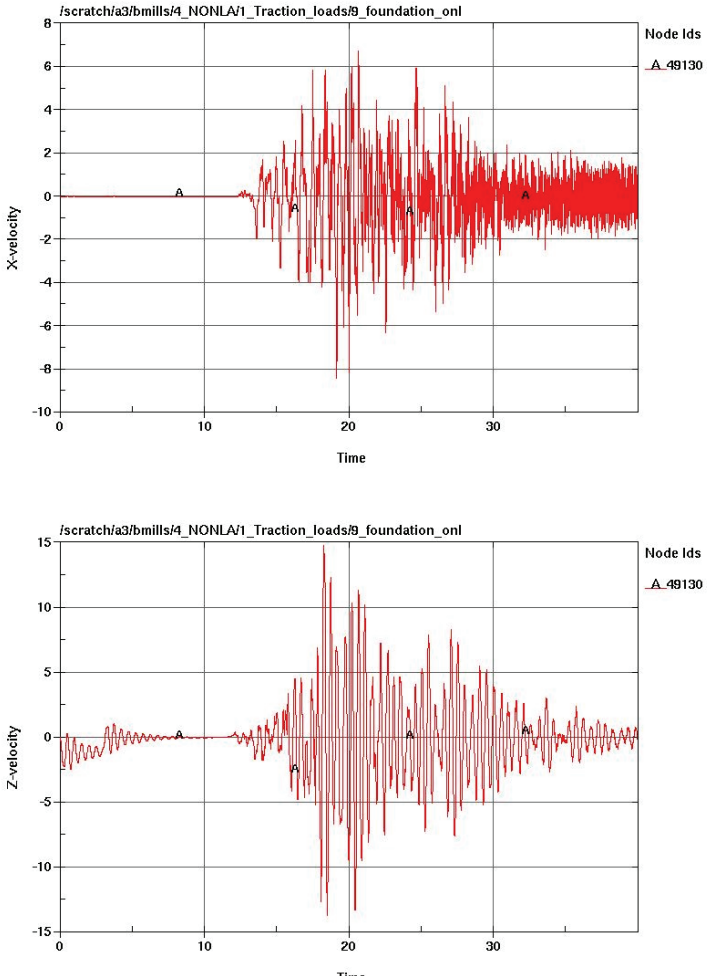


Figure C-4—Applied velocity loads—displacements.



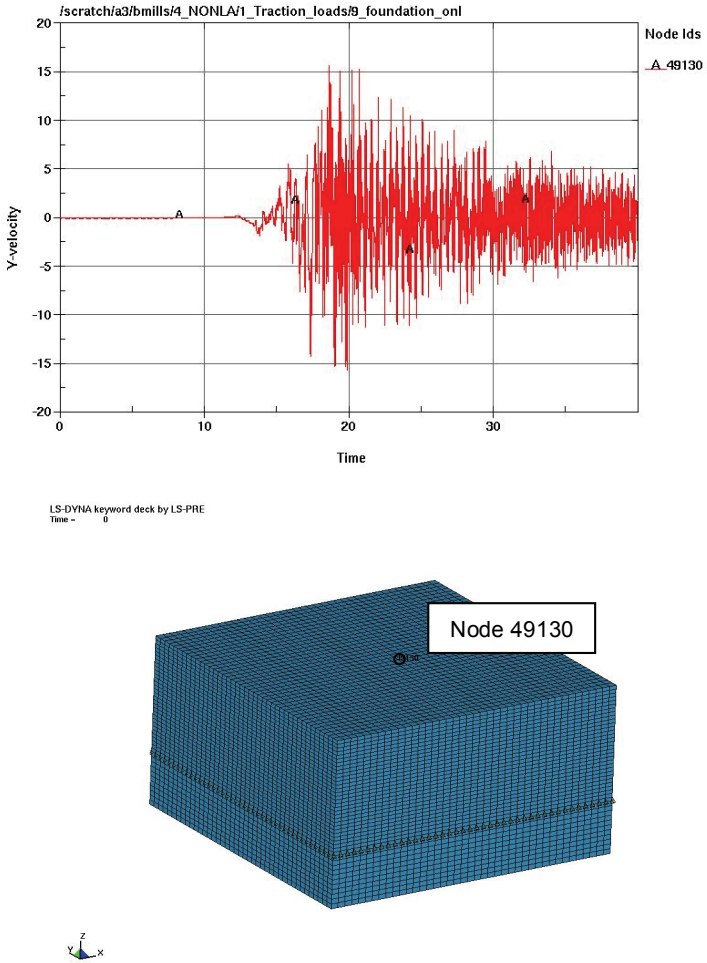
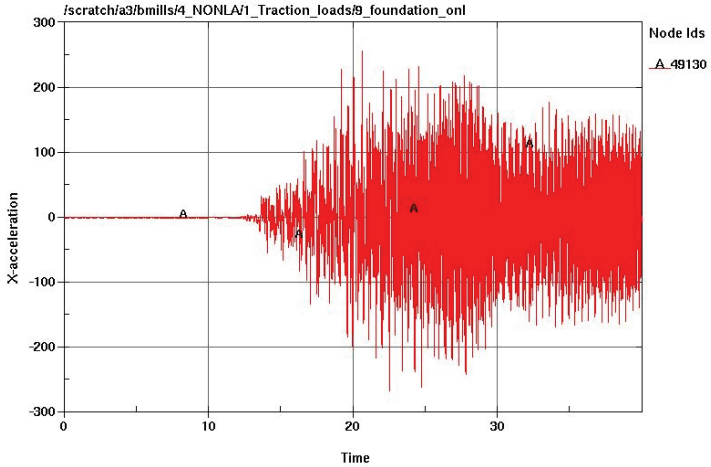
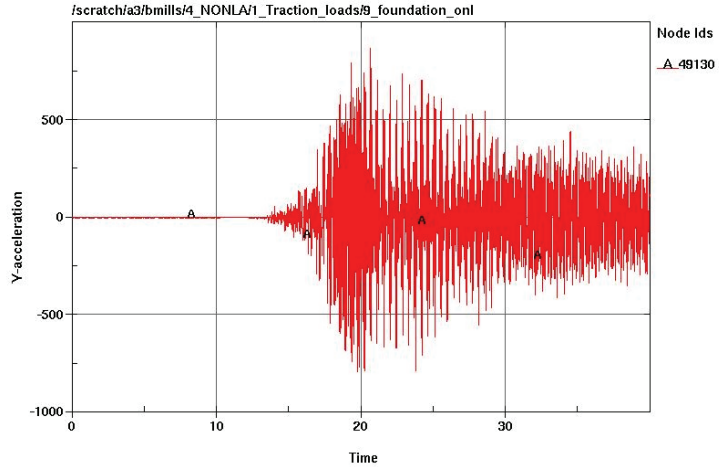
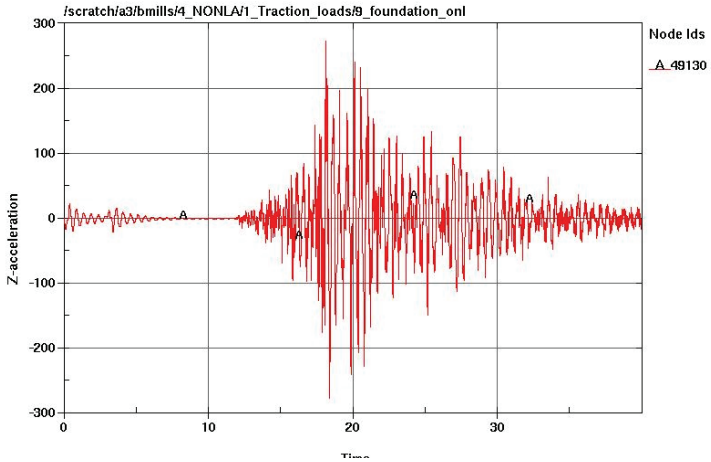


Figure C-5—Applied velocity loads—velocities.







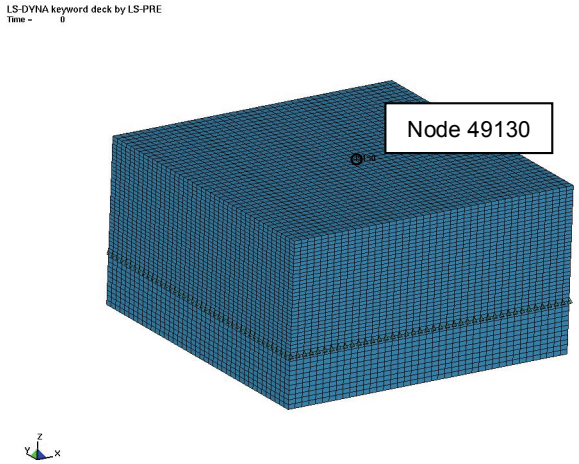


Figure C-6—Applied velocity loads—accelerations.

Appendix D—Fast Fourier Transform Plots

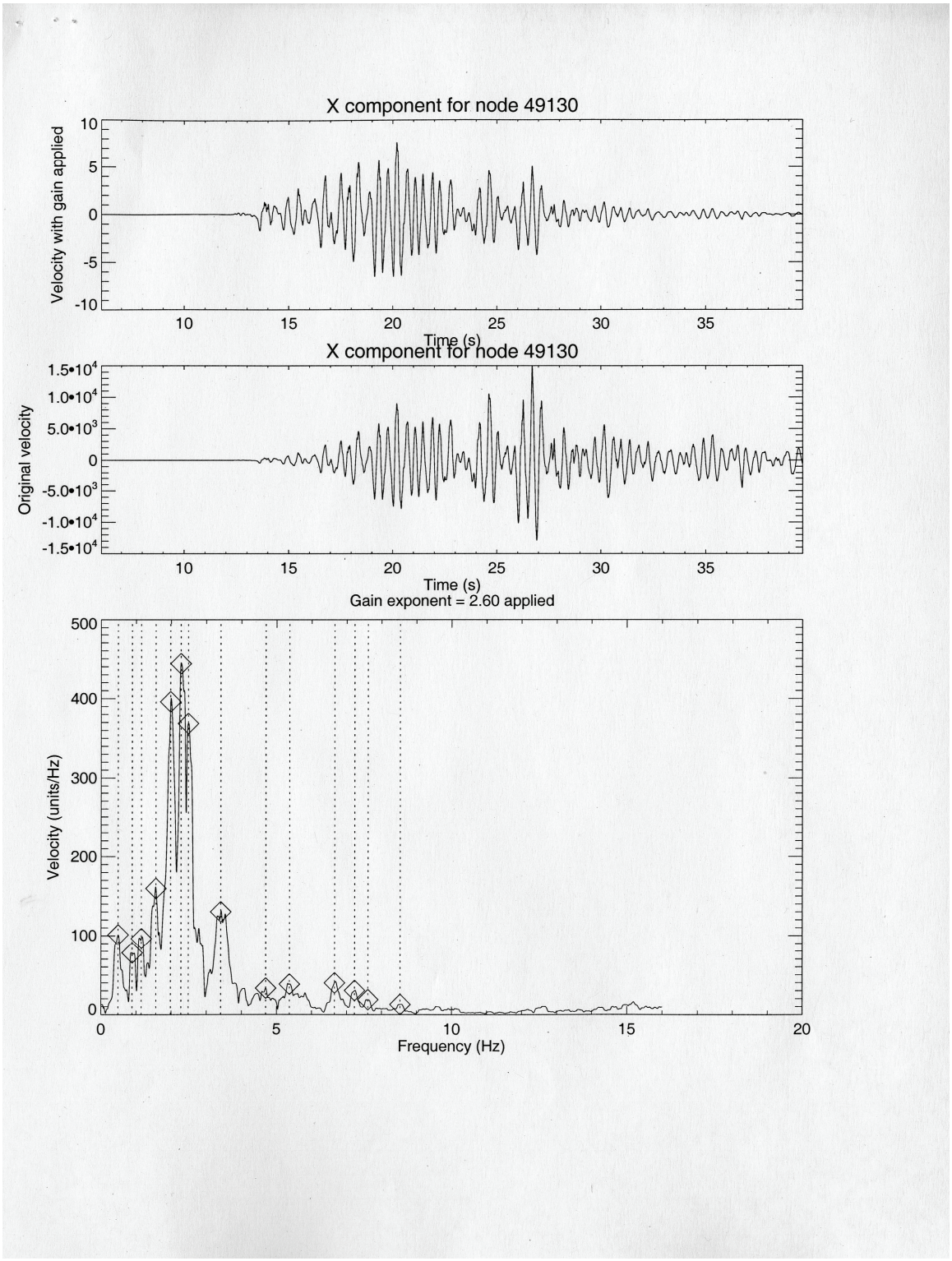


Figure D-1—Fast Fourier transform plots – traction loads, X component

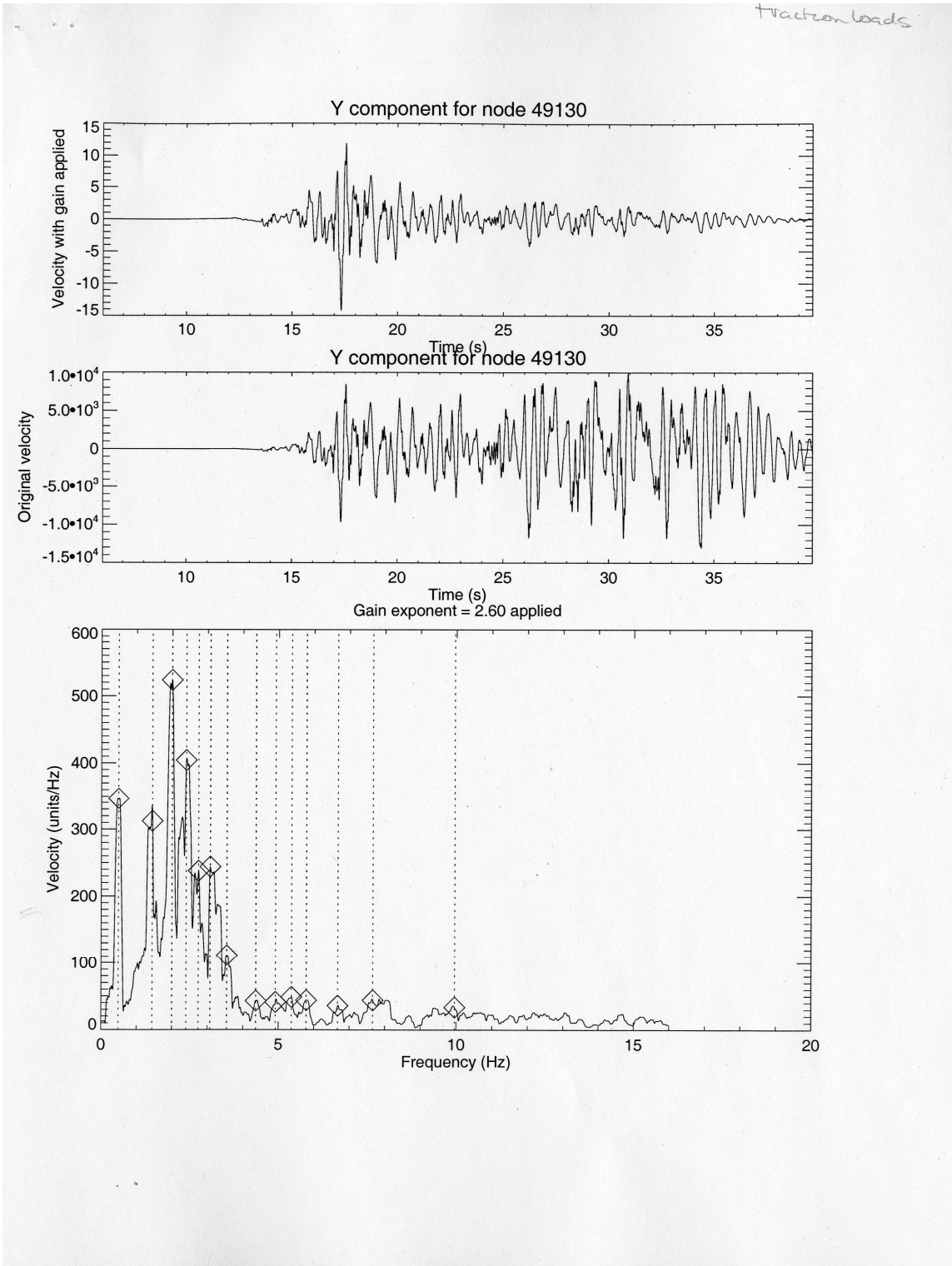


Figure D-2—Fast Fourier transform plots – traction loads, Y component

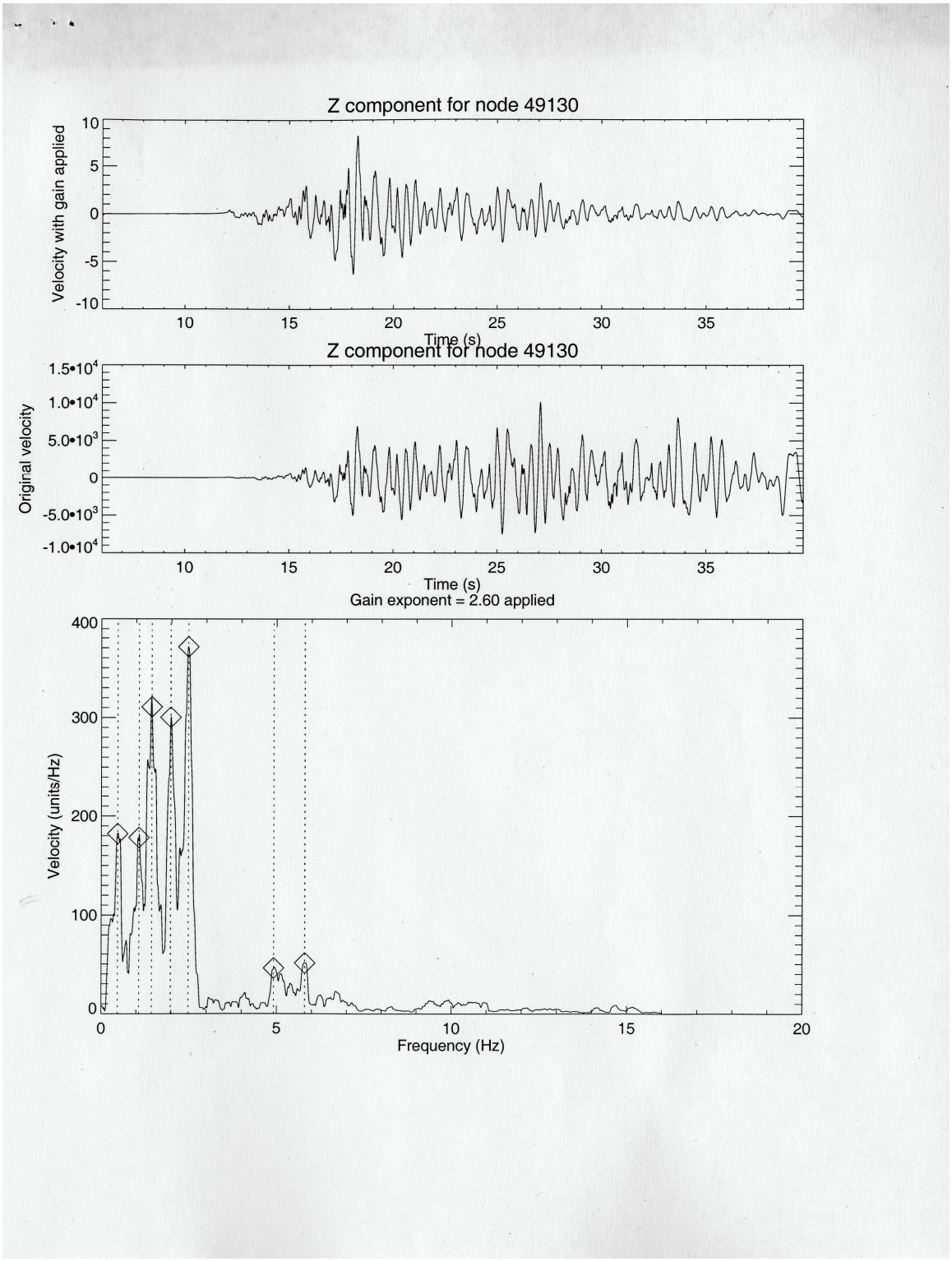


Figure D-3—Fast Fourier transform plots – traction loads, Z component

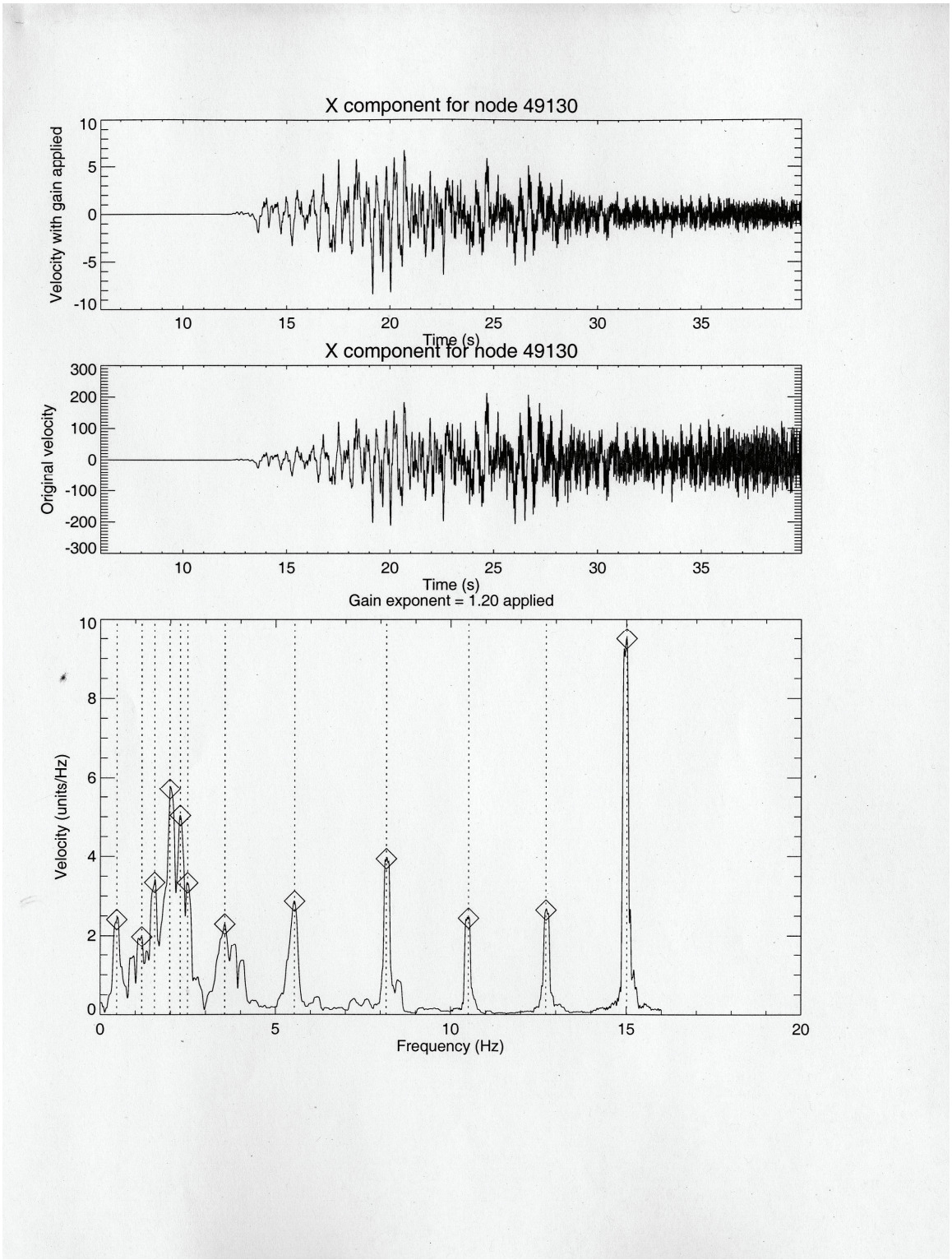


Figure D-4—Fast Fourier transform plots – velocity loads, X component

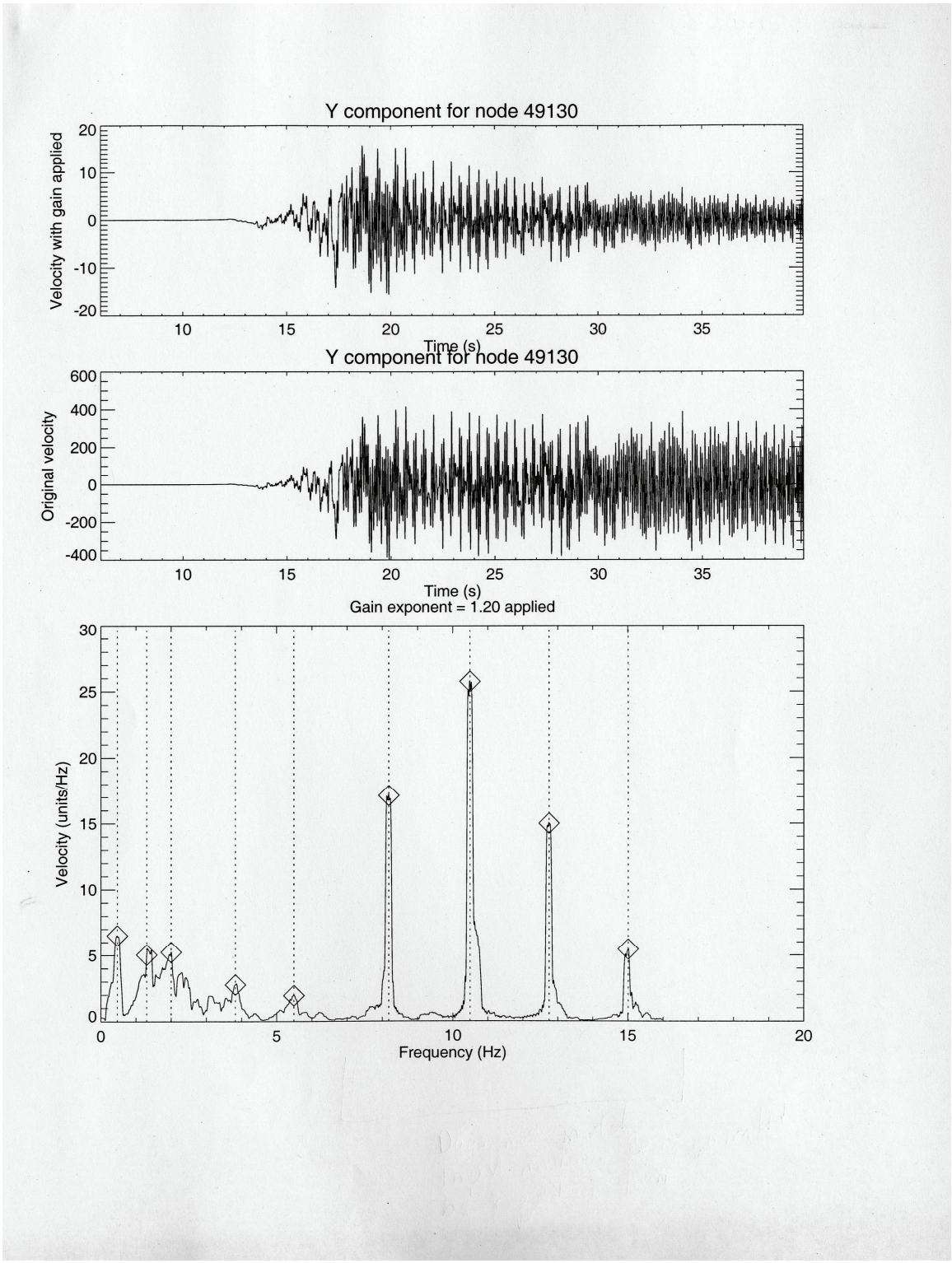


Figure D-5—Fast Fourier transform plots – velocity loads, Y component

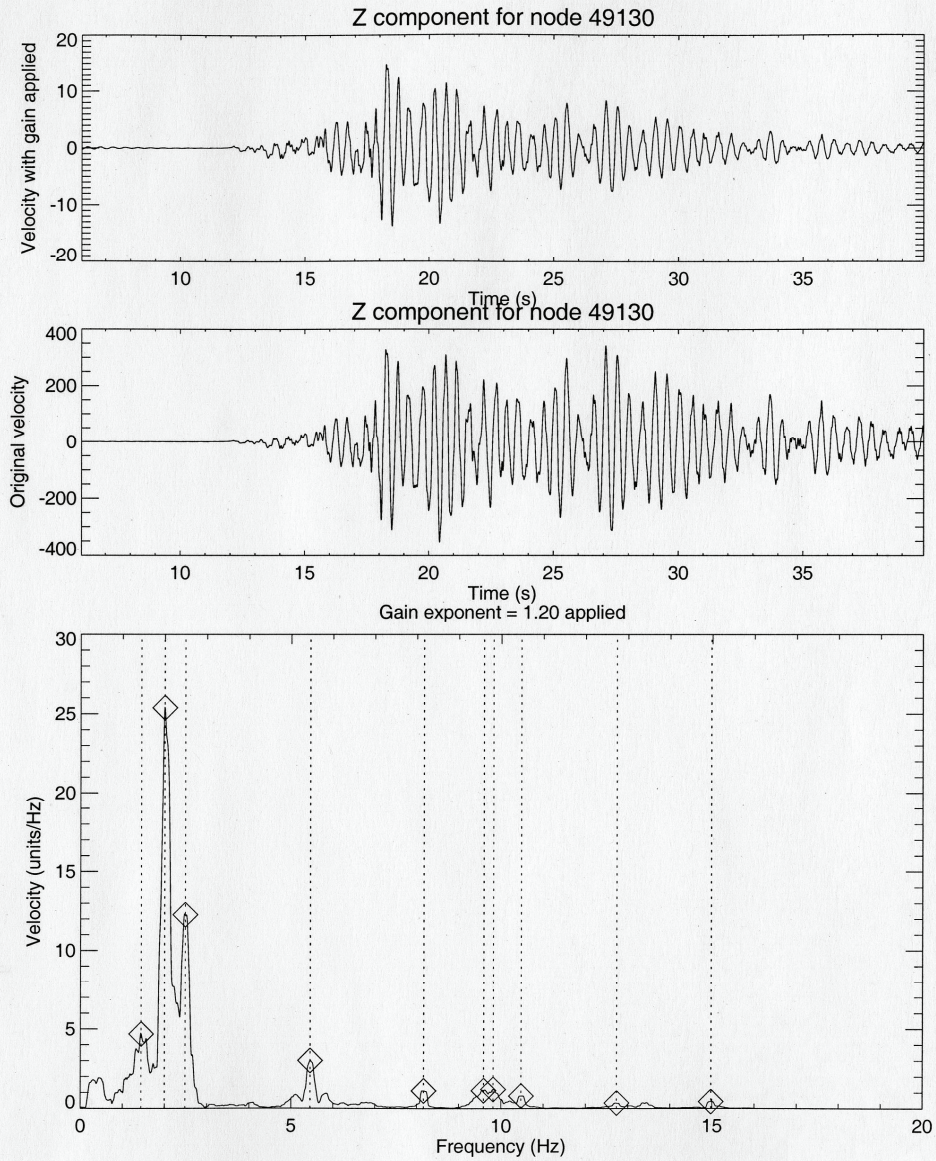


Figure D-6—Fast Fourier transform plots – velocity loads, Z component

Appendix E—Response Spectra Plots

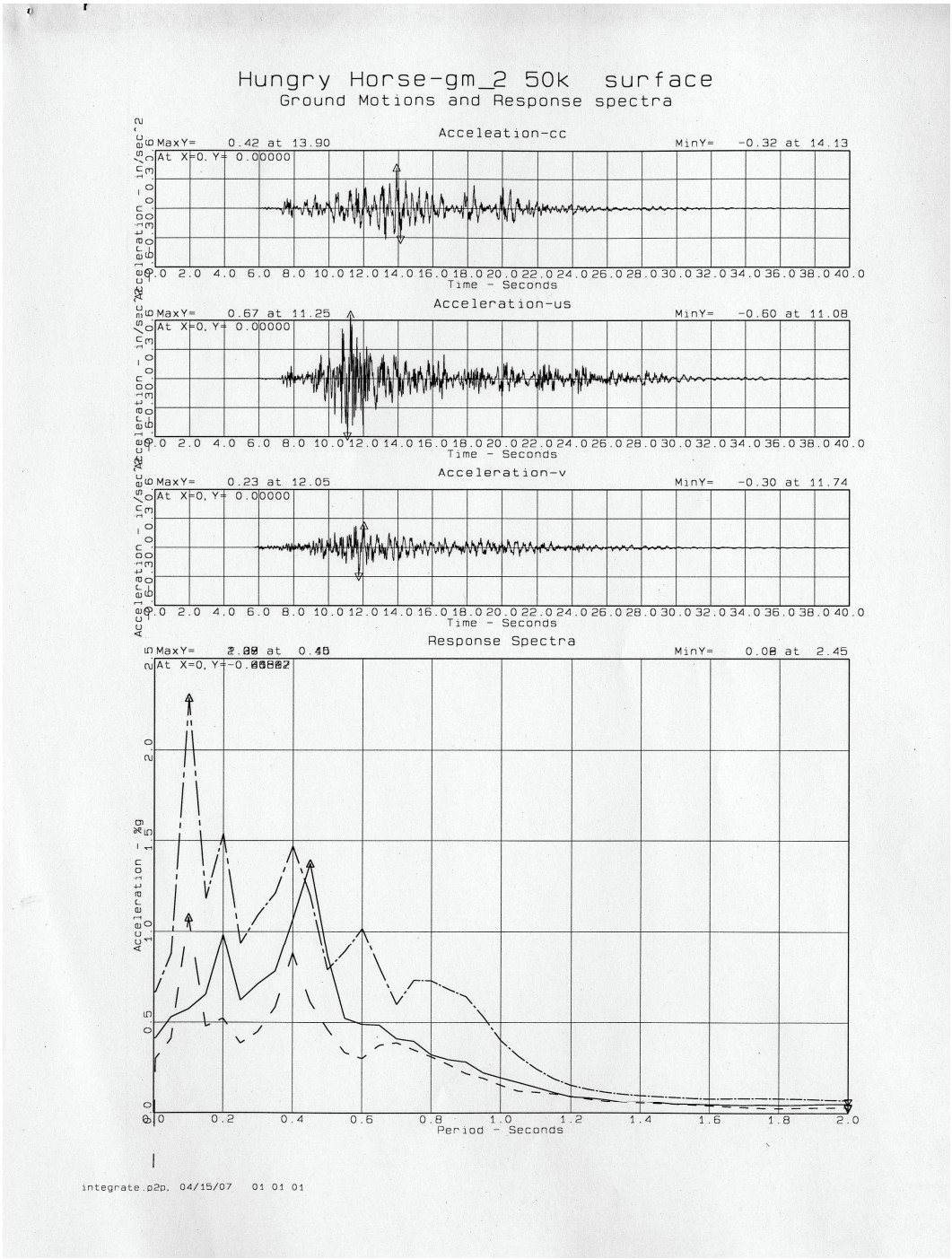


Figure E-1—Acceleration response spectra plots – target motions

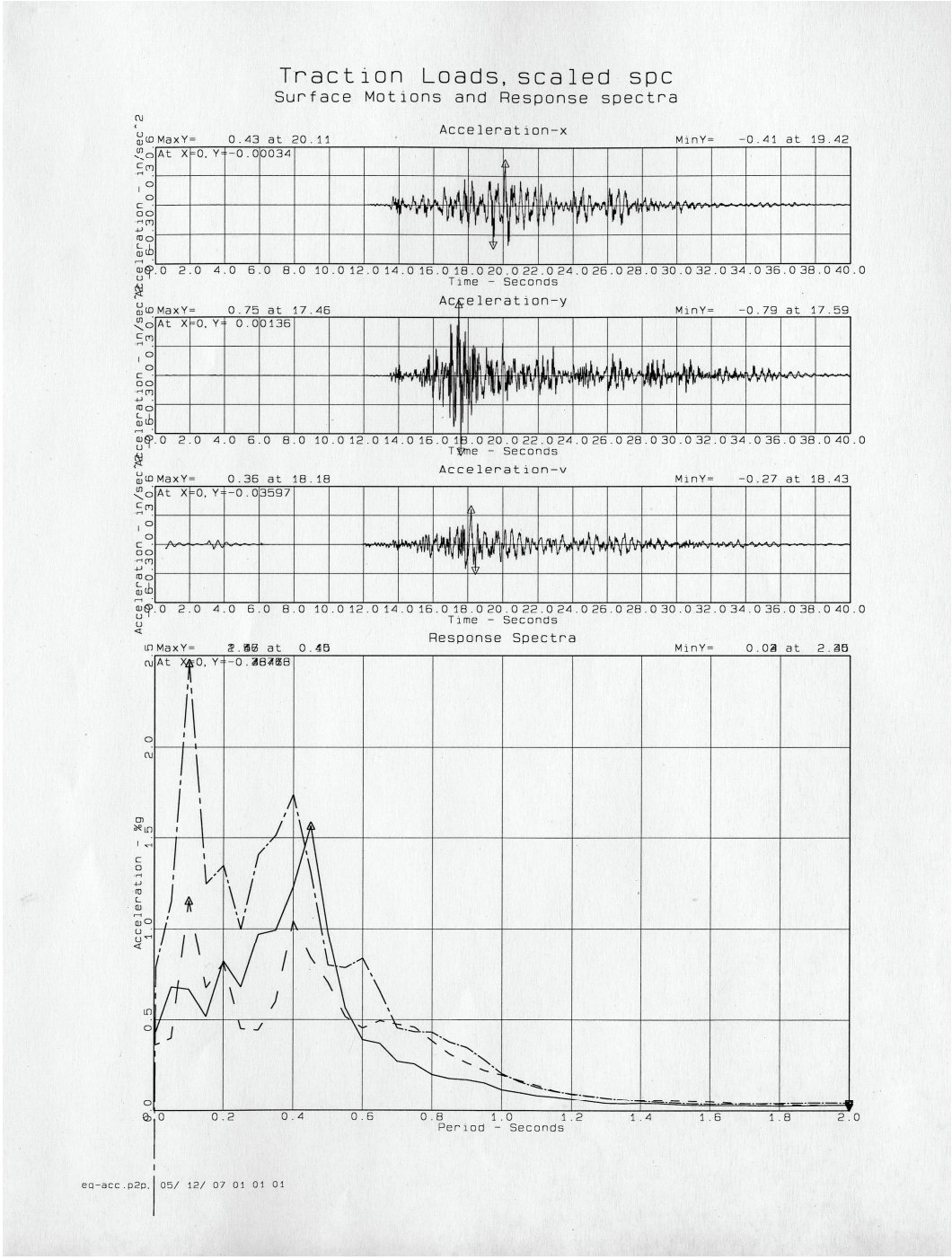


Figure E-2—Acceleration response spectra plots – traction loads

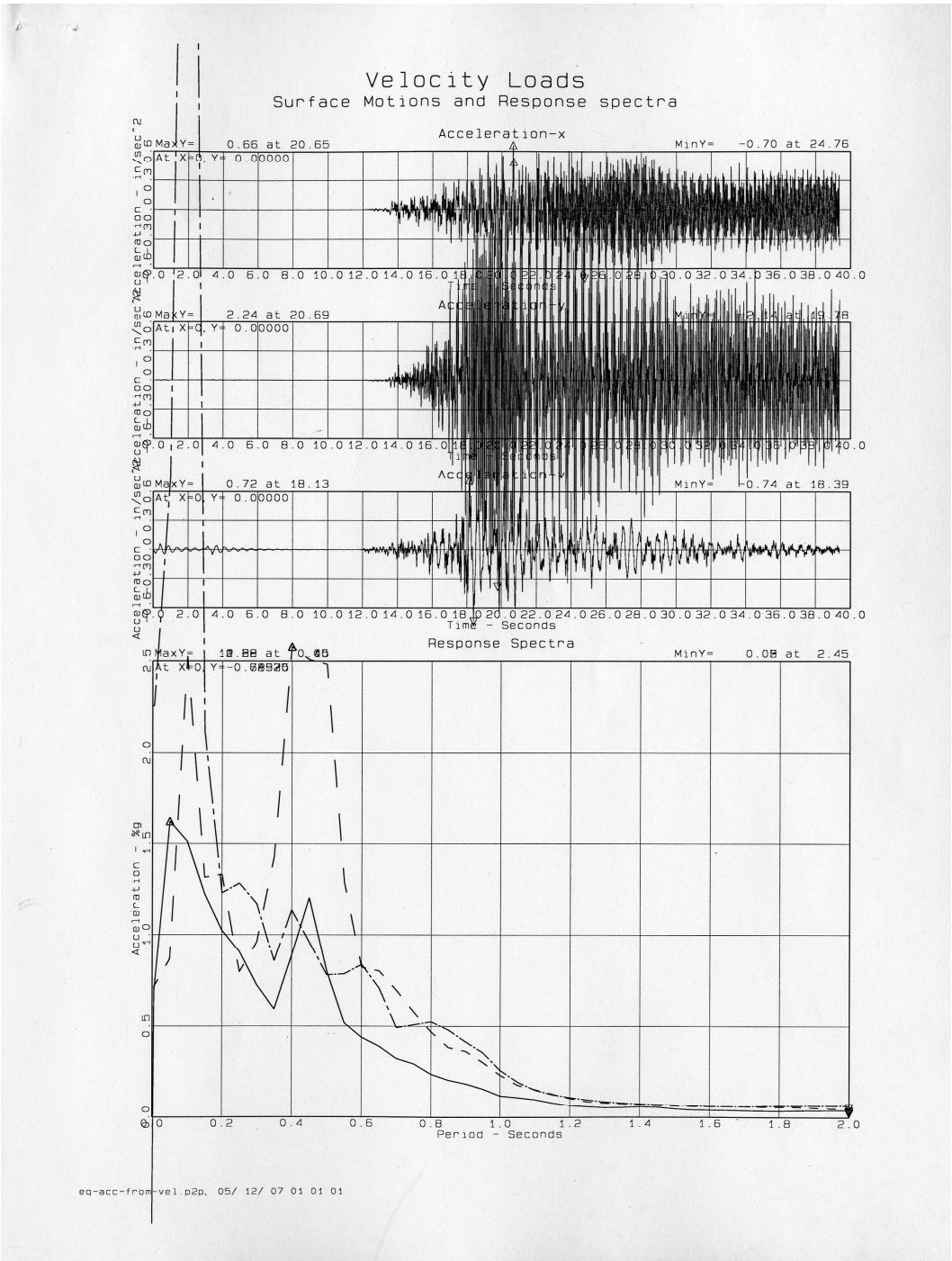


Figure E-3—Acceleration response spectra plots – velocity loads

Instructions

- Calculate scale factor: Vertical motion Horizontal Motion

  $E = \frac{E(1-v)}{(1+v)(1-2v)}$

  $$F(t)_z = \left[\frac{2E' A_i}{C_p}\right] v_z(t)$$

  $$F(t)_x = \left[\frac{2GA_i}{C_s}\right] v_x(t)$$

- faceset is defined in TrueGrid

- *load_segment_set_nonuniform (version of LSDYNA: ls971)
  1,2,20.196
  0,1,0,0

- Gravity run, extract spcforc

- In d3hsp file: mass of model

- Calculate F=ma, modify vertical spcforc values

- Note: in my full model of Hungry Horse Dam, I also have slight discrepancies in horizontal forces, LSDYNA will have to give us more accuracy (Dynamic relaxation has the same problem)

- Command to run FFT program written by Dan O'Connell to read nodout file
  - run_modal_mtap_spectra
  - Note: use nodout in LSDYNA to save nodal information at small time steps (0.0001)

- Compute Acceleration Response Spectra