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Engineering visualization for seismic structure analysis

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ABSTRACT: Visualization for earthquake engineering is discussed. Data analyzer is the basic concept of the reported visualization system. Any kinds of data can be retrieved from a motion movie and analyzed. The data structure and presentation technique are proposed in a prototype of the visualization system.

1. INTRODUCTION

The recent developments on the computer graphics are providing very good graphical environment for the earthquake engineering. Visualization helps to us visual understanding the physical phenomena in addition to logical understanding by numbers. An important point of the visualization is that we can see the things that normally can not be seen. This aspect is not mentioned well when a scientific/engineering visualization is talked. For a static analysis, visualization is in common practice as known "pre-post processor" of structural analysis. For dynamic fluid analysis there are many visualization examples including an animation of the results. But there are few examples of visualization tools in the earthquake engineering.

General purpose visualization software requires many unnecessary handlings of data and computer power. So specialized visualization software for the earthquake engineering research is requested. The visualization tool requested should be able to handle both the results of earthquake response analysis and the observation records of earthquakes.

So we surveyed the capability of the computer graphics and made a prototype of an Earthquake Engineering Visualization (EEV) software called EODAS (Engineering Oriented Design Assistant System). That gave us confidence on usefulness of the EEV and possibility of the future developments.

The EODAS was made to cover the dynamic phenomena in civil engineering. But main interests are on the earthquake engineering field.

2. VISUAL ASPECTS OF EARTHQUAKE ENGINEERING

In a daily procedure on the response analysis, we draw many diagrams to study the results. Time history diagrams and diagrams of maximum acceleration, velocity and displacement are very common. But it is difficult to understand how structures behave by just watching time history diagrams without a motion movie of a structure. Until recently motion movie is taken very occasionally because it took several hours to make the motion movie. But recent computer technology made possible to see it on computer display in real time. And we can easily change the view point and the internal variable to see.

There are many internal variables to study. The variables depend on the elements. E.g., stress, strains are defined in the solid elements. Shear forces, bending moment and axial force are done in a beam element. Crack, damage parameters are defined in non-linear solid element so on.So large storage is required to achieve the EEV.

To view these variables, different expressions are required. And there are some little difference on the expressions for beams, slab, wall, truss, solid ground, pile, tunnel, anchor, etc. For example, shear force of a beam can be expressed by color contour but also by a conventional diagram along the beam element. Maximum acceleration, velocity and displacement are basic variables and most interesting for building design. Not only viewing the data and viewing the results of checking but also analyzing data are necessary. For example we often check the points where stresses are lower than a certain value.

So it is important to provide good analyzer of data that helps making engineering decisions. It is preferable if the EEV system provides the ability to write reports, i.e., it would be an integrated data analysis tool that can work with drawing and word processing software tools.

3. BASIC CONCEPT OF VISUALIZATION

There are two objectives to use the computer graphics technology, i.e., presentation and data viewer. The major role of EVV is a data viewer and the presentation is the secondary purpose.

The EVV should provide the means to analyze results of response analysis and data of observations. So engineers and researchers can understand not only by logic but also by visual intuition.

Basic concept of the EEV is a data base retrieval system that has a good graphical user interface that is specialized for earthquake engineering. In our EVV system (EODAS), the motion movie is a base presentation. The data are retrieved in any figure or diagram by pointing the moving picture, because in the most cases, we want to see the behavior of the vibration first. Then we want to examine the details.

In the motion movie, we can operate the EEV as video movie. E.g., slow motion, fast forward/backward motion and stop motion at any point are available. In addition to that we can change the viewpoint and what to see such as stress, strain, etc.

4. DATA STRUCTURE OF EEV

4.1 *Data Classes*

Data Classification

The data are classified into three categories. They are a configuration data, cosmetic data, variable data. The following section explains the details.

Configuration Data

Configuration data could be stored in two ways which a solid modeler or analysis program uses. Since EVV deals the results of analysis, it is convenient to use the data structure that the most of the structure analysis software uses. Among the many analysis methods, the data format of the finite element method (FEM) is used because the FEM data format can be easily extended to any other analysis method such as the finite difference analysis, the boundary element analysis and the distinct element method so on.

In the FEM, any shape object is divided to a small element that consists of nodes. The element can be presented by nodal coordinates, node-element connectivities, so any kinds of shape can be introduced with same manner of FEM. It is, however, not efficient way if the element has different concept such as a distinct element, rigid element, etc. To avoid these, many elements that are not used in an ordinary FE analysis are introduced as new types of visual elements. They are a circle plate, a sphere and marks to represent boundaries, special parameters (damage mark, etc). Sphere and circle are defined by a center coordinate and radius. Mark is also defined by a center coordinate with normalized shape definition that can be enlarged by scaling factor. Rigid body element is also defined by the same manner.

Cosmetic Data

A beam element is defined by two nodes and the cross-sectional area and moment of inertia so these data do not give the shape data of the element. Therefore we add the data defined details of the shape (e.g., H-shape, box shape beam, etc) and called it a cosmetic data.

There are another cosmetic data. They are color and line type of elements. All these cosmetic data can be added to the structural data that are transferred from the analysis data.

Some of the cosmetic data can have the default value. For example, color of the element can be defined by the material data (elastic modulus, etc) in structural analysis. This is very convenient since we can check material properties on a picture.

Variable Data

Variable data can be the results of response analysis or the observation record of earthquake. These data require huge storage.

We show a typical case. Assuming the response data include stress and strain of elements and acceleration, velocity, displacement of each node and the number of element and nodes are 10,000 in 3 dimensional analysis. The storage size of an element variable is 1,920k bytes (6 components x 8 Gauss points x 10,000 elements x 4 bytes). The storage size of a nodal variable is 240 k byte (6 components x 10,000 nodes x 4 byte). Total 4.45 M byte for stress, strain, acc., vel. and displacement for each time step. If the number steps are 1,000, 4 G bytes storage is required. This is just for one case of analysis. It is not easy to obtain this size of storage in the most of computers with the current technology.

4.2. *Data Storage*

Here few strategies to reduce the storage size are mentioned.

Two byte integer data approach: Data can be normalized by the maximum value at each time step if the variable has the same order of the value. Using "integer*2" for each datum and "real*4" for a maximum value, data storage can be reduced to a half (2.23M for the above example). This method can not be used if the orders of values are not same, e.g., when shear forces and bending moment are mixed in the same storage. Those data must be in a separate file.

When stress and strain are transferred to nodal values, the required storage is 237 k byte. So its reduction rate is 1/8. Then total storage is 600k bytes(240k*5/2). This method can be adapted to 2 and 3 dimensional elements. But smoothing must be carefully done notifying the discontinuity of the variables.

The strain can be calculated from the displacement simultaneously when it is displayed, if a computer has enough speed. The stress is also calculated if the problem is linear.

The data files are classified into two categories. One is the primary files in which the raw data are stored. The other is secondary file in which the data can be reconstructed from the primary file. For example the time histories at any point and mean stresses are in the secondary file.

5. WAY TO VIEW

5.1 *Movement*

Movement is expressed by deformed shape of the model, so coordinates of the each node (or referenced coordinate) $X_i = S_1 * (x_i + S_2 * u_i + S_3 * v_i)$ where X_i is the coordinate on the display, x_i is the coordinate of the original configuration, u_i is the deformation, v_i is a variable that can be any internal variable such as shear force or bending moment. This value is useful and is mentioned later.

5.2 *Global View of Internal Variables at arbitrary Time*

Stress, strain, force, etc can be viewed with contour on the surface of the element in the motion movie. Color contours easily give more insight about internal variables. Color contour can be generated by many ways. Gouraud shading method is often used and provided by many graphical engines that is equivalent to interpolation by a linear shape function. If the high order element is used the Gouraud shading can not be used to interpolate the nodal value. The contour can be drawn for each-element-variable or smoothed-variable. The booth can be used for the different purpose.

5.3 *Time History at an arbitrary Point*

Time history can be retrieved at any point of motion movie. The data in the view window can easily be drawn while the motion picture is displayed but drawing the whole time history may take time for data preparation. This is caused the raw data are stored in the space domain at a time step so the data for all step must be collected from whole data in the primary file. The collection is done as a background job. The time history in the window can be used while the whole time history is prepared. But once it is collected stored in the secondary file , it is easy to retrieve at the next time.

The many styles of figures are provided in the time history since the figures are most often used. Each style is treated by a separate module so it is easy to add and to modify the drawing module.

5.4 *Maximum Value of Variables*

Since the maximum acceleration is used for the design inertia force, the figure of its profile is most often drawn. Again there are many styles of the figure are used so a very flexible tool for drawing is provided. The tool should be able to edit the figure in any ways.

There is an override figure that can be used to know the vibration behavior and the maximum value of the variables as shown in Fig. 1. The figures of the maximum value can be drawn with the configuration of the model.

The maximum value diagram become very complicate when the model is a large 3 dimensional model. So it is necessary to extract the important part of the model. This can be done by many approaches. We propose to reconstruct a simple configuration file. According to this model, the necessary maximum values are extract from the original response data by referring the original configuration data.

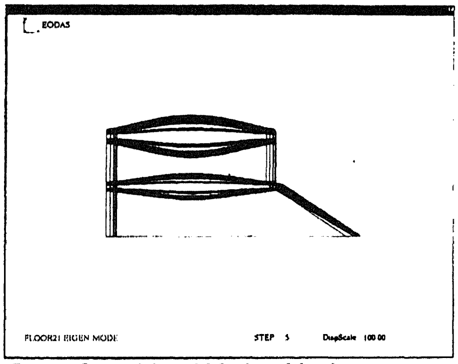

Fig. 1 Override of Motion Movie

5.5 *Comparison of Data/Results*

Comparison is common practice in studying data. There are comparisons of time history and spectra at deformation profiles at any time, maximum values of the different cases, result of analysis and experiment, etc.
In XY-diagram, it can be achieved by drawing the data into one figure.

In deformation profile, two figures can be overlapped with the same deformation scale. The one of the figure is drawn by the wireframe. But there is no direct way to compare a color contour plot.

The two figures can be drawn in the side by side or the difference of the two contours can be drawn. It is convenient if there are rulers that can be in the display and placed at any place to measure the values e.g. length between nodes, deformation at nodes, difference of deformations and any internal variables.

It is also convenient if we can place and move a guide lines at any place. The above ruler should be able to measure the distance of these guide lines as well.

5.6 *Data Analysis/Review*

Spectrum analysis is often used for studying dynamic data. Response, Fourie and power spectra are examined in the many case of seismic engineering. Therefore it is good if we can obtained the spectrums at any point of a motion movie at any time step. This can be easily achieved. The procedure to obtain them is as follows. We can choose any time step moving a slide bar while we watch the motion movie.

Any point can be located by a mouse device at any point on the motion picture. Then list of the internal variable is displayed so we can choose one of them. Then spectrum, time history on raw numbers is displayed. We can switch the figures among the spectrum, time history or raw numbers by just pressing a bottom in the display.

Filtering is another necessary tool for dynamic data analysis. There are some cases that earthquake record has some noise or that we want to study behavior of a certain frequency range, specially in the case of observation data. Therefore lowcut, highcut and band-pass filter are provided. To make easy to handle data, the time step is sometimes skipped. But this is not allowed if the wave has large high frequency components and the acceleration data are integrated to obtain velocity or displacement. Therefore a check tool is provided. That shows the difference of the time history of the displacement from the original wave data. With this tool influence of filtering and tailing problems can also be checked. To study the vibration characteristics of the structures, transfer functions are obtained by specifying two points in the motion movie.

There are many other possibilities to use the EVV. Data check is one of them. Color presentation of material properties is the easiest to make and very useful. We can check colors corresponding the material properties such as elastic modulus, density, porosity, nonlinear parameters, etc.

To check the mass density, we can solve a static problem with a gravity force as an external load. But there is an easier way to achieve this. We can show a size of mass by a mark such as a cubic or sphere for each direction including the rotation.

6 PRESENTATION TECHNIQUE

6.1 *Shape*

The shape is drawn in 3 dimensional wire frame for just the shape, a flat shading surface for the material distribution or a Gouraud shading surface for the contour of the internal variables. All these are drawn by the 3 dimensional polygon of the graphic library. Graphical manipulation such as zooming, parallel transfer and clipping of the shape are done using the graphic library so the benefit of the speed of the graphic engine is obtained.

6.2 *Color*

Color representation is used for draw contour of variables. This can be easily achieved using the Gouraud shading features of the 3 dimensional graphic library that is provided by the most graphic engines(1). Caution must be taken when the high order of the shape function in the FEM is used for the variables. The rendering features can be used to show the configuration of problems but it should not be used with color contour since it changes the color. If the high order of polynomial finite element is used, the color must be determined by the shape function as $R(x,y,z) = N_i(x,y,z)R_i$ where R is color at any point, N_i is the shape / interpolation function, Ri is the nodal value of the variables.

The choice of the color is also important. There is not linear relationship between color and value of the variable. In the most of the case, red is for compression and blue for tension of stress. Rainbow color is the best choice of color distribution.

To look at the specific range of variable, the only interesting range can be drawn in a contour. The range outside of the interesting can be colored with two colors for the upper and the lower ranges.

The distribution of the material properties is expressed by the flat shading. The wire frame with hidden line is drawn by the flat shading with the background color.

Lighting is a useful feature of the graphic library to the model realistic. We use this feature to draw the shape of the model but not used to draw the contour plots because it changes the color distribution. There many attribute for lighting and these are difficult to adjust if we avoid the influence to the contour color. On the other hand, it is necessary to show clearly the details of the structural shape. For example, a H-shape beam is hardly seen without lighting feature.

6.3 *Flag Diagram*

A flag diagram shown in Fig. 2 is used to represent earth pressure, shear force and bending moment of a beam, etc. To represent the flag diagram, a special 4 node element is introduced. In this element each two nodes has the same coordinate (x_i) but different values at nodes. Same displacement is applied to each two nodes represented by u_i in the above and a different value v_i.

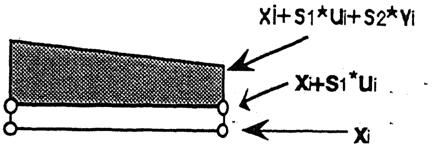

Fig. 2 Flag Diagram

6.4 *Mark / number*

Marks are used to express a condition of variables such as cracks, yield points and cosmetic parts (actuator and exiting point) including boundary condition. The mark is defined by the coordinate and the connectivity as same as a finite element. But displacement is defined only at the one point of a mark. The position of a mark is defined at the center coordinate of the mark. The center coordinate is defined by the relative coordinate from any nodes. An example of the mark is shown in Fig. 3.

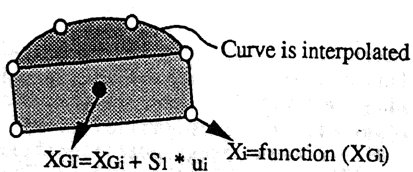

Fig. 3 Example of Marks

Numbers are also displayed but in 2 dimensional manner. The left-bottom coordinate of number is defined as same as the mark's definition.

6.5 *Motion Movie/Animation*

The high speed of the graphic engine allows us to draw the motion movie (animation) of a wire frame model and a surface model. With the surface model, a color contour plotting is also can be drawn as the motion movie. The drawing speed is the fastest in the wire frame model and the others are slower. So the wire frame model can be used if the color or contour is not important.

To draw the motion movie smoothly, the huge data should be kept in the computer memory. It is impossible to keep all data of the time steps. Therefore a view window is introduced as illustrated in Fig. 4. It has a data table in the computer memory and displays picture of any time which data are in a data table. In the automatic stepping mode, the view window moves forward in time. Once we stop the time marching or rewind the data , the view window stop. The view window can not be moved backward.

To obtain the real time motion movie, speed of file access is critical point in addition to the speed of the graphic engine.

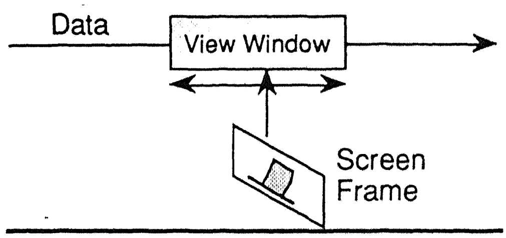

Fig. 4 View Window

The camera command is the command that records the motion movie into the video recorder. To do this, the figures on the computer display must be converted into the video format. This can be done using a frame-scan converter or a network video server. The latter takes more time but obtains the better picture. In the both cases the video recorder is controlled by the EVV software.

7. EXAMPLES

7.1 *Eigen-mode/Frequency Analysis*

Fig. 5 shows a vibration mode of a building. The mode is shown as the structure is deformed proportional to the amplitude of each mode at a time step. In this problem the vibration of slab was important. It is a serious problem for the hi-technology factory. So the mode viewer is often used to analyze the slab motion that is caused by the traffic vibration, impact load and machines, etc. The viewer is used for the ordinary structure analysis as well. It is easy to find the important movement (mode) by watching the motion movie of the modes even in the very complex structures.

An example of override presentation of the eigen-mode is shown in Fig. 1. This figure can be drawn for the results of the response analysis and the observation data so that the profile of the maximum response can be easily obtained. If the input motion is filtered for a certain frequency band, its modal characteristics can be seen. This approach is often used to analyze the observation data.

The frequency response is also shown in the same manner. The frequency of the input load can be continuously changed using a slider so it works as same as the vibration test machine. But in this viewer, the distribution of stresses and strains can be easily observed.

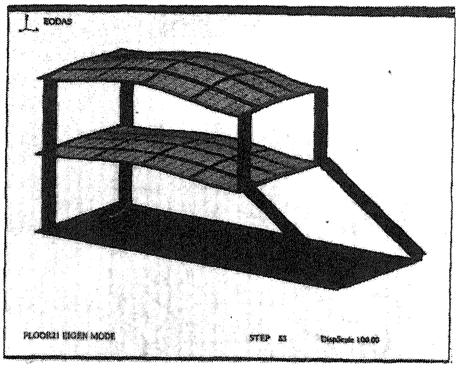

Fig. 5 Eigen-mode Movie

7.2 *Time domain Analysis*

This is the example of the most basic feature of EVV. The motion movie is shown with contours of shear stress of the ground and material properties of the building in Fig. 6. But the ground and the building are modeled by the 3 dimensional solid element. The contour distribution at any section can be seen. The color mapping of the internal variable can be changed manually. So if specific range of the stress is interesting, only that area can be drawn by color contour. Fig.7 shows how to specify the domain to draw the contour for the soil-structure-interaction problem. In this figure a building is shown by the 3 dimensional beam element in the four sub-windows from the different viewpoint. To specify a region to draw in the contour plotting, the region is surrounded by a wire frame of a cubic. When the region is determined, the internal variable in a list is chosen.

The contours are drawn for stress, strain, etc and the secondary data such as mean stress, stress ratio so on. The number of variable types becomes over 100 including the secondary variable. User defined variable may also be necessary.

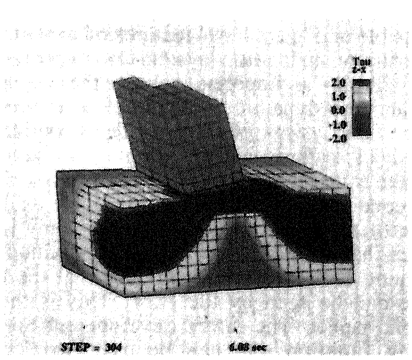

Fig. 6 Contour on 3 D Solid Element

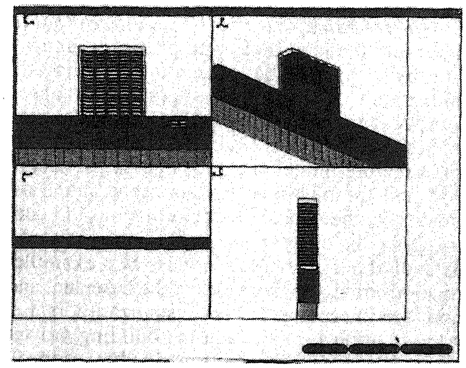

Fig. 7 Selection of 3 D Region

7.3 *Earthquake Record of Building*

Fig. 8 shows the visualization of the observation data of an experimental building for an active mass-damper (AMD). The building left-hand-side shows the movement of the building while the AMD works. The observation data are taken at the first, fourth and top floor. The movements of the other floors are interpolated by the observation data. The rotation of floor is calculated assuming the slab is rigid. The right-hand-side building shows the movement without the AMD that is obtained by response analysis subjected to the input motion at the basement. The deformation can not be seen in the real structure when it is subjected to an earthquake. The deformation can be seen only by the EEV. Fig. 9 shows the top view of the same experimental building.

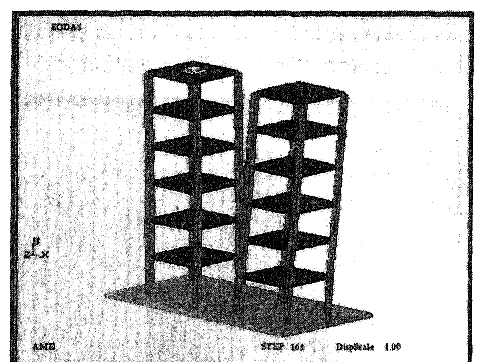

Fig. 8 Eathquake Record of a Building

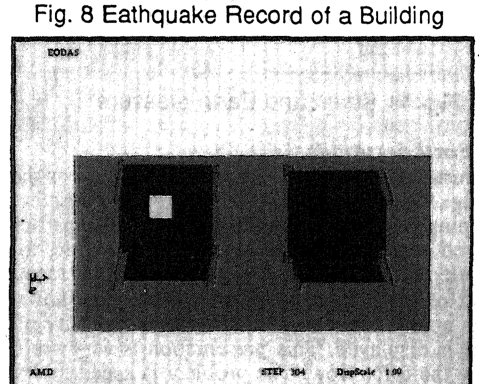

Fig. 9 Topview of AMD building

7.4 *Earth-pressure on Soil-Structure-Problem*

Fig. 10 shows the record of earth-pressures along a tall building by using the flag presentation (yellow flag). The movement is obtain by integrating the observed acceleration and add to the configuration data that is automatically done by the EODAS. The configuration of the soil-structure-model was prepared by the same way of FEM and the observation data are inputted as the deformation of the nodes. The deformations of node that does not have the observation data are interpolated with the data of the observation nodes. For example the deformations of all the floor except the basement and the top floor are interpolated. This visualization is used to study the relationship between the building movement and the earth-pressure behavior. So the strain of the ground is calculated from the deformation as shown in Fig. 11. Fourie spectrum and transfer function can be obtained at any observation points that can be specified on the display.

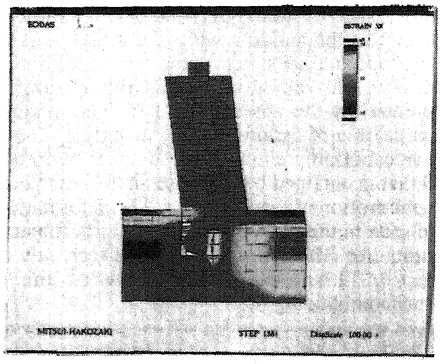

Fig. 10 Earth-pressure Observation

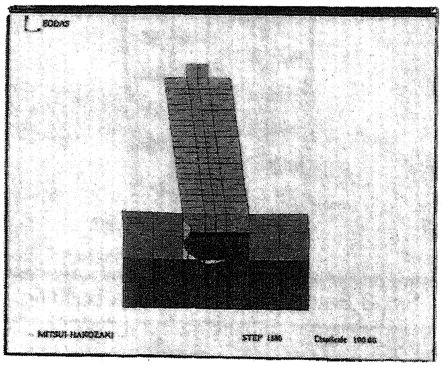

Fig. 11 Strain and Earth-pressure

7.5 *Particle Analysis*

The result of the distinct element is visualized as shown in Fig. 12. The figure shows that the particles are dropping from the top basket of a silo. The particle is colored according to the average force acting to the particle. Fig. 13 shows the other way to present the result of the distinct element method.And shows the force acting between particles where intensity of the force is displayed. This presentation is very useful to know the force flow. The problem is speed to draw a circle and sphere that takes more time than a box or a solid surface.

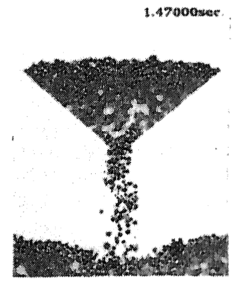

Fig. 12 Distinct Elment Method

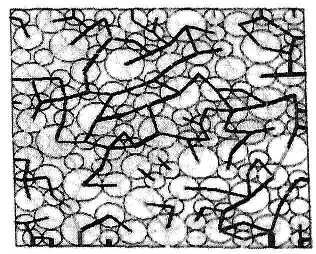

Fig. 13 Stress Flow through particles

7.6 *Moving Boundary*

Fig. 14 shows an example of the cosmetic data. It is not an earthquake problem but a dynamic problem. The object at the center is the moving body sliding down along the U-shape bobsleigh course. The body is defined by a mark and its movement is obtained from an analysis. The decorative parts are the U-shape boundary and trees.

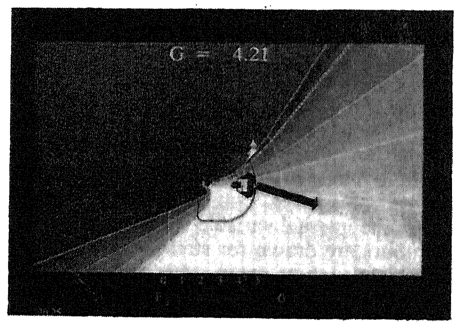

Fig. 14 Cosmetic Element

8. Concluding Remarks

The possible and 'must-have' features of an earthquake engineering visualization system are reported. The system will play an important role for the engineers to understand the dynamic behavior of structures. The prototype EEV system, EODAS, made us confident that data analysis features will provide new horizon to the earthquake engineering where they can examine the data as they conduct an experiment and analyze its data. In the case of an analysis they can study many internal variables that are not able to directly obtained in the experiment. It should also be noticed that the unseen variable can be seen by the EEV. This is the most important aspect. The future development may be a reporting function that can be used with a word processor and/or desk-top-publishing.