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COMPARATIVE STUDY OF SEISMIC ANALYSES FOR PIPING SYSTEMS

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ABSTRACT

In this paper, the effect of earthquake loading on the design procedure of piping systems is determined. An example of a typical expansion pipe unit is analysed with three different methods: a static analysis and harmonic analyses with acceleration on the mass and harmonic displacement of the support. It is shown that standard procedures can lead to a conservative design and prevent the optimization of the results. An optimum design can be obtained by using supports with adequate damping and stiffness, and hence, the loading on the piping system can be minimized.

Keywords: Seismic loading, harmonic analysis, pipeline design, response spectra.

INTRODUCTION

Due to its location on the Mid-Atlantic Ridge, seismic activity is common in Iceland and earthquake engineering is a well-known subject. Earthquake risks maps have been constructed that predict the ground acceleration in different parts of the country. All structures, including pipelines, are designed according to a particular design code. In general, the European design code Eurocode 8 is used in structural earthquake design. Iceland receives part of its energy from geothermal sources. Generally, geothermal power plants are situated in high seismic activity areas and therefore earthquake loading is a critical factor in the structural design. The predicted ground acceleration at a geothermal area can be as high as 0.1 g which is generally thought to be enough to cause damage to weak construction (Arnold and Reitherman, 1982). Significant increased cost is involved in the design, making and installation of structures where seismic loading is taken into account. In particular, the supports for piping systems are made bigger and stiffer to withstand the loading. Therefore, it is of utmost importance to have a simple standard procedure for seismic design of piping systems. The focus here is on the design of geothermal piping systems.

Piping systems are supported either on concrete supports above ground or they are underground. In either case, they can be sensitive to ground movements and cyclic loading due to their natural frequencies.

Three basic methods are available for analysing the seismic response of piping systems: a static load analysis, using the design response spectra, a harmonic analysis, and a time history analysis. In general, a static analysis is sufficient if one is interested in the long-term response of a structure to applied loads. However, if the duration of the applied load is short, such as in an earthquake, a dynamic analysis is more accurate.

In the past, the design of piping systems has been based on elastic response spectra where the response of a simple damped oscillator for known earthquakes is used to determine the so-called pseudoacceleration of the structure. The method was developed in the 70's for piping systems for nuclear power plants (ASME, 1984). The design response spectra method was originally proposed by G.W. Housner (Housner, 1941). His work was based on research by M.A. Biot (Biot, 1933). These methods are still standard procedures in earthquake design (Olson et al., 1994), (Bratt, 1994). During the past few years, earthquake research has been based on performance-based design methodologies or reliability based design (Buzzurro et al, 1994), (van de Lindt et al, 2000). However, because of the complexity of these new methods, traditional analyses are still widely used. Modal analysis which includes correct support stiffness can be a complicated analysis. Therefore, designers use the static analysis with the maximum response spectrum acceleration as loading, for simplicity. In this paper, it is demonstrated how that simplified approach can affect the design.

The motivation for this work was the structural design of piping systems for a geothermal power plant where a static loading approach resulted in increased weight and increased stiffness of the systems. It is a well known fact that increased weight and increased stiffness is contradictory to the preferred design against seismic loading (Arnold and Reitherman, 1982). The weight is an important factor in the design of structures to resist earthquake motion. As the mass increases, the inertia forces increase. As a result supports are made stronger and pipe stiffeners are used to take up the increased loading. Furthermore, the piping system needs to be constrained against displacements in more places which in turn increases the stiffness of the system. An increase in stiffness, means higher natural frequencies for the structure. Thus, natural frequencies can get close to excitation frequencies of the earthquake. Design against seismic loading also leads to increased operating stresses for thermal loading and internal pressure.

The purpose of this work is to assess the validity of the static loading approach by comparing the results of a static and a harmonic analysis. In particular, the reaction forces and the pipe displacements at the supports will be compared. Furthermore, it is investigated how the design method chosen by the design engineer can affect the outcome of the design.

COMPUTATIONAL ANALYSES OF PIPING SYSTEMS

Static Analysis

In a static analysis, an equivalent static force is computed by multiplying the response acceleration by the mass of the system according to Newton's second law. Hence, an increase in the mass means an increase in the applied force. The particular response acceleration is determined from a design response spectrum. Figure 1 shows a typical site-specific design response spectrum for a geothermal area with high seismic activity and the the response spectrum predicted by Eurocode 8. The site-specific spectrum is based on a 500 years return period (Bessason et al., 1996). Since the natural frequency of the structure is unknown in a static analysis, the maximum value of acceleration determined from the response spectrum is used. Referring to Figure 1, the maximum value of acceleration is 1.1g which occurs at frequency above 5 Hz. For a frequency below 5 Hz, the loading is given by:

$$1.1(0.2\omega)^{0.7} \tag{1}$$

where ω is the frequency. Thus, a harmonic analysis is favorable to determine the natural frequency of the structure.

The process of a harmonic analysis is described in the following section.

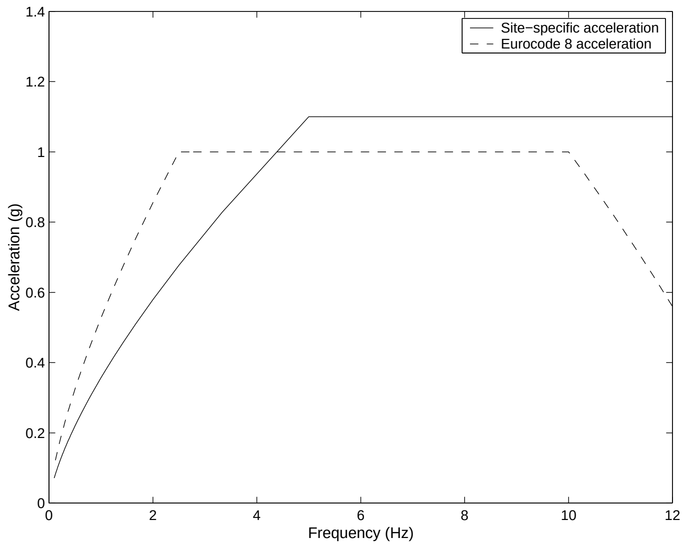

Figure 1. Design Response Spectra

Harmonic Analysis

A harmonic analysis determines the steady-state response of a linear structure to loads that vary sinusoidally with time. The systems response is calculated for several frequencies.

The first step of a harmonic analysis is a modal analysis. A modal analysis extracts the natural frequencies and mode shapes of the system. The equation of motion for an undamped system, expressed in matrix notation is:

$$[M]\{\ddot{u}\} + [K]\{u\} = \{0\} \tag{2}$$

where $[M]$ is the mass matrix of the structure, $[K]$ is the stiffness matrix, $\{\ddot{u}\}$ is the nodal acceleration and $\{u\}$ is the nodal displacement. This can be expressed as an eigenvalue problem whose solution gives the natural frequencies and modal shapes of the system. The n_{th}harmonic response is:

$$\{u\}_n = \{v\}_n cos\omega_n t \tag{3}$$

where $\{v\}_n$ is the eigenvector representing the mode shape of the n_{th} natural frequency, ω_n is the n_{th} natural circular frequency and

t is time. Thus, inserting equation (3) in equation (2) gives:

$$(-\omega_n^2[M]+[K])\{v\}_n = 0 \qquad (4)$$

which has a nontrivial solution if

$$det\left[[K]-\omega_n^2[M]\right] = 0 \qquad (5)$$

The second step of the harmonic analysis is carried out once the natural frequencies and mode shapes have been determined. The equation of motion is:

$$[M]\{\ddot{u}\}+[C]\{\dot{u}\}+[K]\{u\} = \{F\} \qquad (6)$$

where again $[M]$ is the mass matrix of the structure, $[C]$ is the damping matrix, $[K]$ is the stiffness matrix, $\{\ddot{u}\}$ is the nodal acceleration, $\{\dot{u}\}$ is the nodal velocity vector, $\{u\}$ is the nodal displacement vector and $\{F\}$ is the applied load vector. All points in the structure are moving at the same known frequency but not necessarily in phase. The presence of damping also causes phase shifts. Hence, the displacements may be defined as:

$$\{u\} = \{u_{max}e^{i\phi}\}e^{i\omega t} \qquad (7)$$

where $u_{max}$is the maximum displacement, i is the square root of -1, ω is the imposed circular frequency, ϕ is the displacement phase shift and t is the time. Making use of complex notation, equation (7) can be rewritten as:

$$\{u\} = \{\{u_1\}+i\{u_2\}\}e^{i\omega t} \qquad (8)$$

where $\{u_1\} = \{u_{max}\cos\phi\}$ is the real displacement vector and $\{u_2\} = \{u_{max}\sin\phi\}$ is the imaginary displacement vector. Similarly, the force vector can be specified as:

$$\{F\} = \{F_{max}e^{i\phi}\}e^{i\omega t} \qquad (9)$$

or

$$\{F\} = \{\{F_1\}+i\{F_2\}\}e^{i\omega t} \qquad (10)$$

where F_{max} is the force magnitude, ϕ is the force phase shift, $\{F_1\} = \{F_{max}\cos\phi\}$ is the real force vector and $\{F_2\} = \{F_{max}\sin\phi\}$ is the imaginary force vector. Substituting equations (8) and (10) into equation (6) gives:

$$(-\omega^2[M]+i\omega[C]+[K])(\{u_1\}+i\{u_2\})e^{i\omega t} = \{F_1\}+i\{F_2\}e^{i\omega t} \qquad (11)$$

The dependence of time is the same on both sides and can therefore be removed:

$$([K]-\omega^2[M]+i\omega[C])(\{u_1\}+i\{u_2\}) = \{F_1\}+i\{F_2\} \qquad (12)$$

This equation is solved with the finite element code Ansys for two types of loading, referred to as case 1 and case 2, as described below.

Case 1 A harmonic analysis is carried out where the loading is in the form of ground acceleration. The ratio of the acceleration transmitted to the mass and the amplitude of ground acceleration is known as the transmissibility of the system. For a damping ratio of 5%, the transmissibility of the system has a value of 10.5. Thus, the particular ground acceleration for each frequency is determined from the design spectrum in Figure 1 by using this value of transmissibility. The acceleration is applied uniformly to the entire mass of the piping system.

Case 2 A harmonic analysis is carried out where the loading is in the form of ground displacements. The equivalent displacement for each frequency is computed as:

$$u = \frac{\ddot{u}}{\omega^2} \qquad (13)$$

The displacements are applied to the supports for each frequency. The supports are made of a steel structure with one end attached to the pipe and the other end attached to a rigid concrete support in the ground. The steel support acts as a damper for the piping system and the affect is modeled with a linear spring and damper model; see Figure 2. The amount of loading transferred from the support to the piping system depends on the stiffness of the support.

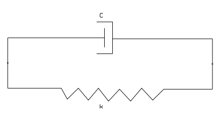

Figure 2. Damper and spring support

DESCRIPTION OF PIPING SYSTEM

A typical above ground piping system is chosen for this analysis. The sample system is shown schematically in Figure 3. The system consists of two straight segments connected with one 90 degree bend to allow for thermal expansion. A rectangular coordinate system is introduced. The horizontal piping system lies in the x,y plane, and the z-axis extends in the vertical direction. Boundary conditions are such that the pipe is rigidly constrained at each end. Along each straight segment, the pipe is supported by steel supports which are connected to concrete supports in the ground. There are two types of supports: one that hinders vertical displacements only and one that constrains both vertical and transverse displacements. There are twelve supports, numbered 1 – 12. Supports numbered 5 and 6 are constrained against vertical displacements but are free to displace in longitudinal and transverse directions. Supports numbered 3,4 and 9-11 are all constrained against both transverse and vertical displacements but are free to displace in the longitudinal direction. Supports numbered 1 and 12 are anchored.

The pipe material is according to standard DIN 17100 and the pipe dimensions are in accordance with standard DIN 2458. The pipe diameter is 711 mm and the wall thickness is 8.8 mm.

The mass of the piping system includes the mass of the steel piping, the piping insulation and the piping fluid. Distribution of mass is uniform and hence uniform loading is applied to the piping system. The seismic forces are applied separately in the two principal horizontal directions of the pipeline, but are never combined. In addition to the horizontal forces, vertical forces are applied. The amplitude of the vertical seismic forces is taken to be one-half of the horizontal forces. In addition to seismic loading, self-weight of the structure is taken into account. Thermal loading and internal pressure are not considered in this discussion.

The calculations are carried out in the commercial finite element code Ansys (Ansys).

COMPARISON OF ANALYSES

Analyses are carried out for a static case, based on design response spectrum, and the two harmonic cases described previously. A comparison of the different analyses methods shows how the choice of an analysis approach made by the designer affects the outcome of the design.

A modal analysis is performed to extract the natural frequencies and mode shapes of the system. Table 1 shows the results for the first ten natural frequencies. A comparison of the results of Table 1 to the response spectrum in Figure 1, shows that the first seven natural frequencies are below the frequency of maximum response.

A representative deformed shape of the system is shown in Figure 4, vibrating at the first mode.

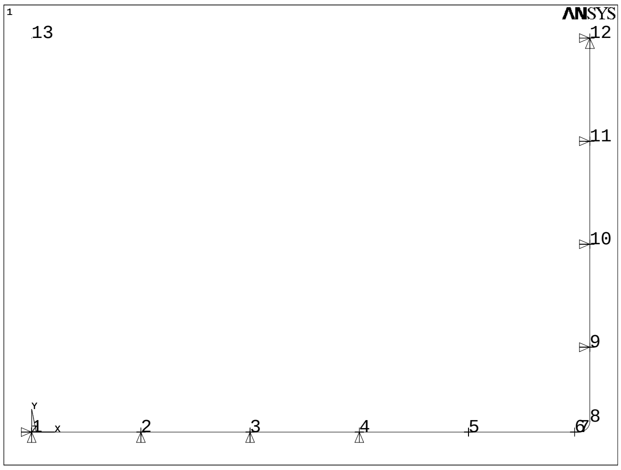

Figure 3. Piping Layout

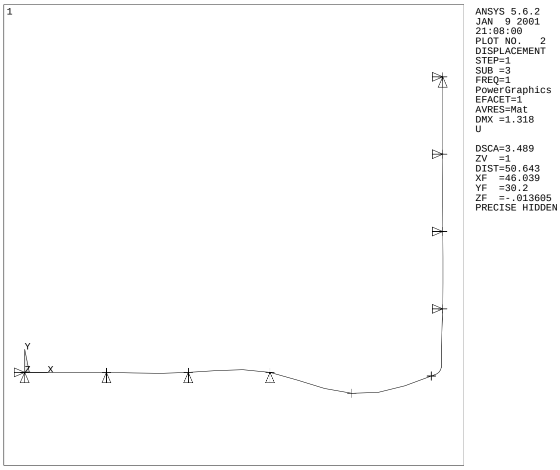

Figure 4. Deformed shape of the piping system

A comparison of displacements in the static analysis and case 1 of the harmonic analysis, is shown in Figure 5. The magnitude of the transverse displacements at supports no. 5 and no. 6 is plotted versus the frequency. Recall, that supports no. 5 and no. 6 are the only supports that allow for transverse displacements. The displacements in the static analysis do not vary with frequency, of course. The static displacement at support no. 5 is about 380 mm, and at support no. 6 it is about 240 mm, whereas, the maximum harmonic displacements are 50 mm and 12 mm, respectively. Hence, it can be concluded that the static analysis gives significantly higher displacements than the harmonic ana-

Mode no.	Natural frequency (Hz)
1	1.0
2	3.2
3	3.4
4	3.8
5	4.0
6	4.1
7	4.3
8	5.1
9	5.4
10	5.5

Table 1. Natural frequencies of the pipeline

lysis. This result can be explained as follows. The lowest natural frequency of the system is only 1 Hz which is lower than the excitation frequency for the acceleration used in the static analysis. Thus, if the design engineer chooses to use a static approach in the design, without knowing the natural frequencies of the system, the consequence is an overdesigned structure with overdimensioned supports.

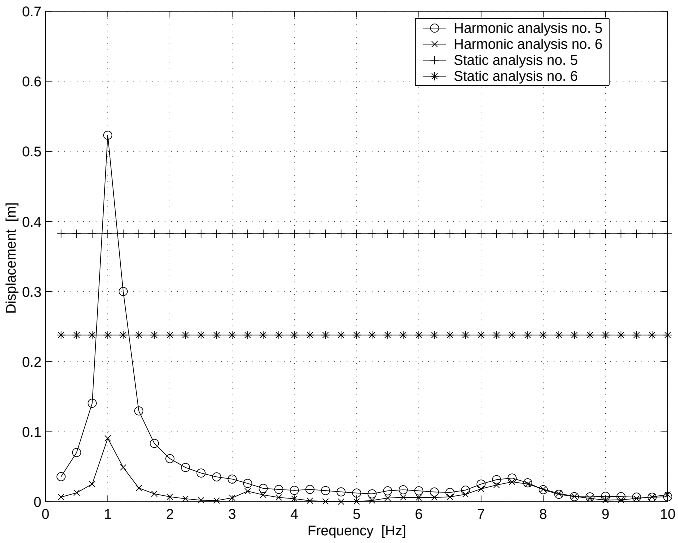

Figure 5. Displacements vs. frequency

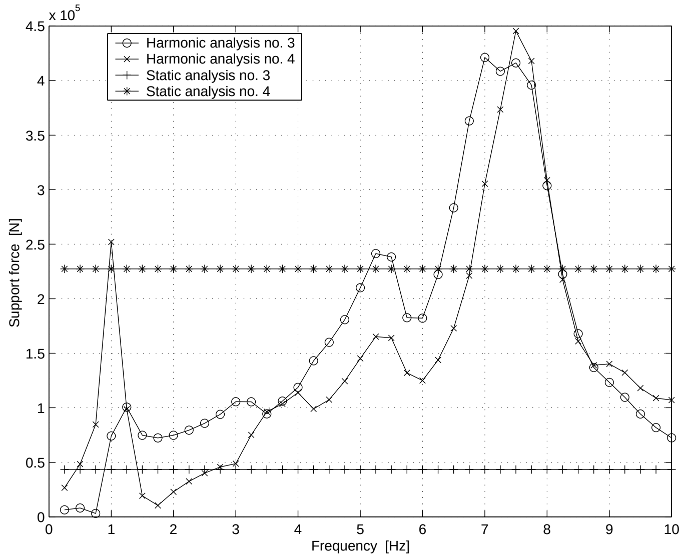

Figure 6. Reaction forces vs. frequency

Figure 6 shows a comparison of reaction forces for supports no. 3 and no. 4 for the static analysis and the harmonic analysis, case 1. Supports no. 3 and no. 4 are chosen here since the greatest reaction forces occur at these supports. The reaction forces for the static analysis do not vary with frequency, of course. The magnitude of reaction force at support no. 3 is about 45 kN, and at support no. 4 it is about 225 kN. The reaction forces for the harmonic case are significantly lower for all frequencies, except, the reaction force at support no. 3 approaches the harmonic result for a frequency of 7 Hz. Again, the results are in favor of the harmonic analysis.

Similar to Figure 5, a graph of computed displacements for the static analysis and case 2 of the harmonic analysis is shown in Figure 7. Again, displacements at supports no. 5 and no. 6 are plotted versus the entire frequency range. Recall, the difference between case 1 and case 2 of the harmonic analyses. Case 2 refers to applied displacements at the supports, whereas, case 1 refers to loading in the form of acceleration on the mass. By applying displacements to the supports, there is a greater difference between the static and harmonic results.

Similar to Figure 6, Figure 8 shows a comparison of reaction forces for supports no. 3 and no.4 for the static and case 2 of the harmonic analysis. A representative result is shown here, but the results vary greatly with stiffness of the support. By increasing the stiffness, the harmonic results will approach the static results.

The tendency of a static analysis is to increase the stiffness which eliminates the possibility of reaching an optimum design.

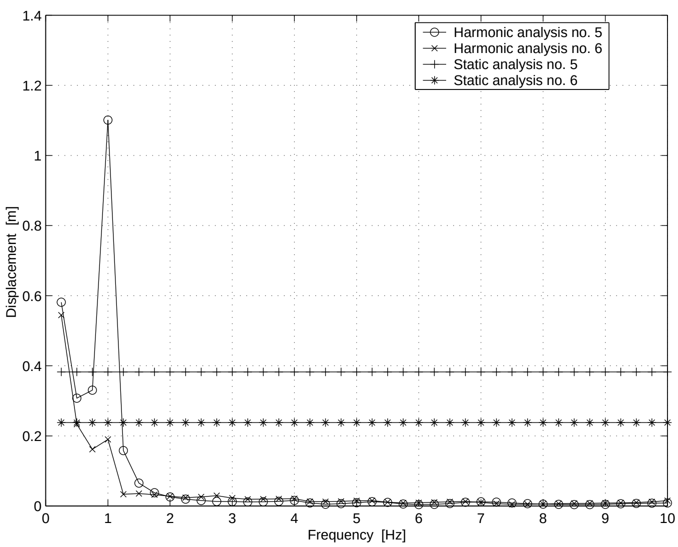

Figure 7. Displacements vs. frequency

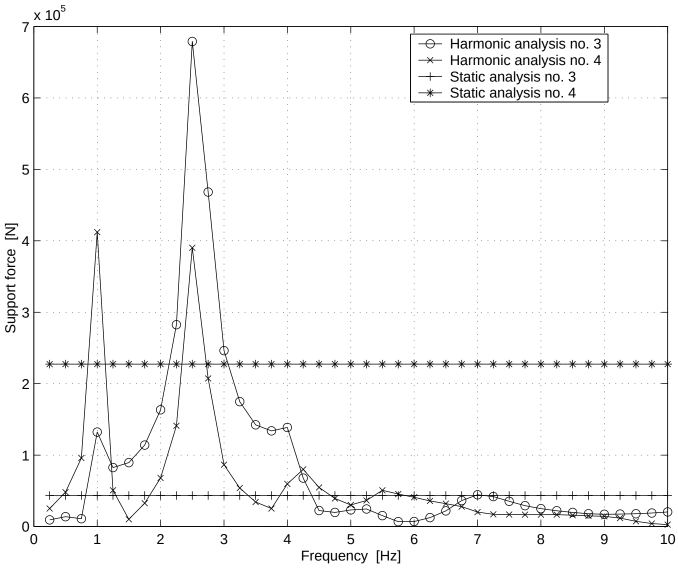

Figure 8. Reaction forces vs. frequency

CONCLUSIONS

The design of piping systems which is based on response spectrum static analysis can lead to an overdesigned system. The loading on piping supports will be overestimated and hence, the supports will be too stiff. This work shows the importance of including the stiffness of the supports in the harmonic analysis. The next step in this work will be construct a finite element model of the support itself and include it in the analysis. With multi-criteria optimum design, the reaction force on the support can be eliminated.

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