Response analysis of pipeline crossing structure with earthquake

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Abstract. Pipeline spanning structure has the characteristics of small overall stiffness, poor resistance to deformation, and large slender-length ratio with poor stability. It is a vulnerable part of long distance pipeline engineering under earthquake action, so it is necessary to analyze the response of pipeline spanning structure under earthquake action. In this paper, the structure model of pipeline span is established through ANSYS, and numerical simulation analysis is carried out under seismic action to explore the influence law of pipeline span structure under seismic action of different pipeline span length and different pipeline span form. The results show that the middle span is the most unfavorable position for pipeline crossing. In the same span, with the increase of span length, the natural frequency of pipeline decreases and the period increases. When the span length of pipeline is fixed, the natural frequency of straight pipeline is obviously higher than that of other pipelines, and the seismic performance is the best. It provides a theoretical basis for seismic design of pipeline crossing structure.

1. Introduction

China is a country with frequent and serious earthquakes. Earthquakes are random, changeable and unpredictable, causing extremely serious damage to human beings. The secondary disaster caused by the earthquake also threatens people's life and property, along with the spread of the pipeline in the "lifeline project", its position in the modern industrial production and people's life is more and more prominent, the earthquake caused the damage of lifeline project affected the people's normal life, caused a huge economic loss. Therefore, it is particularly important to study the corresponding analysis of pipeline crossing structure under the action of earthquake. Based on the elastic beam theory, Guo Haiyan et al. created a mathematical model from three different angles and carried out dynamic response analysis. The main reason for the change of dynamic bending moment is the uneven settlement at both ends of the pipeline. Chen Jun, Li Jie et al. proposed the concept of seismic reliability of pipeline system by combining the mathematical thinking of probability theory, replaced the abstract concept with the mathematical representational concept, obtained multiple failure probability through calculation, and obtained seismic reliability index. T.O. O’Rourke et al. investigated a large number of post-earthquake situations and explored and studied the causes of earthquake disasters. The results showed that the damage of pipelines under earthquake action usually occurred when the earthquake level was above 6. Yan Weiheng and Ma Yawei established a beam-type pipeline crossing model by using SAP2000, and replaced the liquid action in the pipeline with additional constant load. They studied the seismic response by various methods, and found that the seismic action was mainly borne by the pipeline. Strengthening the design of pipeline support can improve its seismic performance.
With the deepening of the research, the domestic and foreign scholars have made a lot of research on pipeline crossing, but pipeline span structure under the action of the earthquake response analysis is still exist deficiencies, so need to under the seismic action of different factors affecting pipeline crossing structure seismic performance, so as to provide theoretical basis for pipeline crossing structure seismic design. In this paper, based on the modal analysis of 20 models with different pipeline spanning forms and different pipeline spanning lengths, seismic time-history analysis is carried out to simulate the response of spanning pipelines under two working conditions of El-Centro wave and artificial wave, and relevant data are extracted. Based on the analysis of the data obtained, the seismic law of pipeline span structure is obtained, and the seismic design suggestion of pipeline span structure is put forward. In this paper, the maximum stress unit is Mpa, and the maximum displacement unit is cm.

2. Finite element model establishment

In order to explore the influence law of different influencing factors on the effect of pipeline crossing structure under seismic action, this study designed and numbered the structural models with the length and form of pipeline as variables. Finite element simulation of all constraints imposed on both ends of the pipeline crossing model, material properties, and so on the parameters such as table 1, model number, such as table 2 model structure as shown in figure 1, the seismic wave selection of EL Centro wave, artificial wave two kinds of working condition, seismic wave as shown in figure 2, according to the more severe earthquake, the earthquake intensity of 8 degrees (design basic earthquake acceleration of 0.3 g), seismic analysis. The Full method in the transient analysis of ANSYS software is used to analyze the pipeline spanning model, and the displacement time response, stress and strain of longitudinal (X), transverse (Y) and vertical (Z) of each model node are obtained.

| Piping materials | Density | Poisson's ratio | Elasticity modulus | Pipe wall thickness | Pipe diameter | Pipe height |
|------------------|---------|-----------------|--------------------|--------------------|--------------|------------|
| Q235             | 7850kg/m³ | 0.3             | 210Gpa            | 12mm              | 508mm        | 1m         |

| Number | Length | A1 | A2 | A3 | A4 |
|--------|--------|----|----|----|----|
| Ship   |        |    |    |    |    |
| Straight | 15m   | A1 | A2 | A3 | A4 |
| 90°    | 20m    | B1 | B2 | B3 | B4 |
| 60°    | 25m    | C1 | C2 | C3 | C4 |
| 45°    | 30m    | D1 | D2 | D3 | D4 |
| 30°    |        | E1 | E2 | E3 | E4 |

Figure 1. Spanning form of pipeline
3. Numerical simulation results are analyzed

3.1. The modal analysis

The dynamic response of the structure under the action of earthquake is closely related to the seismic wave and the structure's self-seismic characteristic, which mainly refers to the natural frequency and natural mode of the structure.

In order to study the different pipeline span length and different forms of pipeline crossing of two kinds of factors affecting pipeline across the shock characteristics of model, using the Block Lanczons method to the 20 kinds of pipeline crossing model for modal analysis, to study the top five order natural frequency, only the straight pipe before five order modal frequency and the span length of 20 meters model before five order modal frequency listed in table 3, table 4, respectively. FIG. 3 (a) shows the first-order natural frequency variation of straight pipe with different lengths, and FIG. 3 (b) shows the first-order natural frequency variation of different pipeline spanning forms with a length of 20 meters, in units of Hz.

| Table 3. First five mode frequencies of straight pipe |
|------------------------------------------------------|
| Frequency No. | A1 | A2 | A3 | A4 |
|---------------|----|----|----|----|
| 1             | 17.67 | 9.14 | 6.23 | 4.51 |
| 2             | 17.67 | 9.14 | 6.23 | 4.51 |
| 3             | 47.04 | 24.74 | 16.95 | 12.32 |
| 4             | 47.04 | 24.74 | 16.95 | 12.32 |
| 5             | 88.40 | 47.36 | 32.69 | 23.87 |

| Table 4. Frequency of the first five modes of the model spanning a length of 20 meters |
|-------------------------------------------------------------------------------------|
| Frequency No. | A1 | A2 | A3 | A4 |
|---------------|----|----|----|----|
| 1             | 9.14 | 5.58 | 4.59 | 4.28 |
| 2             | 9.14 | 7.01 | 6.60 | 6.53 |
| 3             | 24.74 | 15.65 | 12.17 | 11.23 |
| 4             | 24.74 | 16.00 | 12.49 | 11.58 |
| 5             | 47.36 | 27.69 | 22.48 | 20.76 |
It is found by modal analysis that the natural frequency increases with the increase of modal order. (1) From the aspect of spanning form: when the span length of the pipeline is fixed, the vibration pattern basically changes little in the same amplitude, and the vibration form is transverse bending vibration in the horizontal plane, and the stretching vibration of the longitudinal axis is the main vibration. The natural frequency of straight pipe is obviously higher than the other four structural forms. (2) From the aspect of pipeline span length: when the pipeline span form is fixed, as the span length increases, the mode of vibration is basically the same but the amplitude obviously increases, the natural frequency decreases, the frequency decreases and the length increases. In order to make the structure more resistant to earthquakes and improve its seismic safety reserve, the pipeline crossing form should be selected to increase the natural vibration frequency of the structure. Meanwhile, the selection of pipeline crossing length should be appropriate.

3.2. Influence of span length on pipe under El-Centro wave action

3.2.1. Seismic analysis of straight pipe.
The maximum Von Mises stress was obtained from the pipeline spanning model A1 at 4.84s, with a value of 66Mpa, a strain of 0.00032, and a mid-span deflection of 0.75cm. The distribution of deformation, stress and strain across the structure was shown in figure 4. The maximum stress occurs at the mid-span position, and the coordinates of nodes are (3,1.7,-0.4). The displacement time history curves of nodes in the X, Y and Z directions are shown in figure 5.
Based on the analysis of straight pipe models with different spans, it was found that the maximum Von Mises stress was roughly observed in the middle span of straight pipe models, and the maximum stress, maximum strain, and maximum displacement of a1-A4 around the middle span were presented in Table 5. The time history of three-direction displacement of mid-span nodes was summarized in Figure 6.

### Table 5. A1-A4 seismic analysis data

| Number | Time/s | Maximum stress | Maximum strain | Maximal displacement |
|--------|--------|----------------|----------------|----------------------|
| A1     | 4.84   | 66             | 0.00032        | 0.755                |
| A2     | 12     | 190            | 0.001167       | 8.384                |
| A3     | 12.4   | 274            | 0.001332       | 13.305               |
| A4     | 13.7   | 312            | 0.0015         | 14.5                 |

![Figure 6. Time history summary of straight pipe three-way displacement](image)

3.2.2. Seismic analysis of pipeline 90°, 60°, 45° and 30°.

The maximum Von Mises stress of pipeline models of 90°, 60°, 45° and 30° were all around the mid-span. The data of maximum stress around the mid-span of the model were listed as shown in Table 6-9. The time history of three-direction displacement of mid-span nodes is shown in FIG. 7-10 respectively.

### Table 6. B1-B4 Seismic analysis data

| Number | Time/s | Max stress | Max strain | Max displacement |
|--------|--------|------------|------------|------------------|
| B1     | 4.5    | 33.2       | 0.00015    | 0.58             |
| B2     | 5.02   | 193        | 0.00101    | 9.785            |
| B3     | 5.04   | 267        | 0.00136    | 11.325           |
| B4     | 11.38  | 368        | 0.00175    | 22.735           |

### Table 7. Data of C1-C4 seismic analysis

| Number | Time/s | Max stress | Max strain | Max displacement |
|--------|--------|------------|------------|------------------|
| C1     | 5.68   | 50.2       | 0.00023    | 1.189            |
| C2     | 12.04  | 220        | 0.00077    | 11.246           |
| C3     | 14.64  | 257        | 0.00102    | 11.221           |
| C4     | 12     | 261        | 0.00135    | 12.6             |
### Table 8. D1-D4 seismic analysis data

| Number | Time/s | Max stress | Max strain | Max displacement |
|--------|--------|------------|------------|------------------|
| D1     | 5.02   | 47.7       | 0.00022    | 1.04             |
| D2     | 11.86  | 213        | 0.00053    | 7.995            |
| D3     | 14.62  | 260        | 0.00076    | 13.247           |
| D4     | 14     | 278        | 0.00084    | 18.954           |

### Table 9. E1-E4 seismic analysis data

| Number | Time/s | Max stress | Max strain | Max displacement |
|--------|--------|------------|------------|------------------|
| E1     | 9.42   | 38.8       | 0.00018    | 0.971            |
| E2     | 5.66   | 220        | 0.00073    | 6.324            |
| E3     | 8.62   | 252        | 0.00086    | 9.956            |
| E4     | 10.06  | 287        | 0.00136    | 21               |

3.3. Influence of span length on pipe under artificial wave action

In the time history of artificial wave action, the maximum Von Mises stress was observed in each pipeline model around the midspan. The time history of three-direction displacement of mid-span nodes is shown in FIG. 11-15 respectively. The data of maximum stress were listed in Table 10-14.
Figure 13. Time history curves of three-direction displacement of 60° pipe

Figure 14. Time history curves of three-direction displacement of 45° pipe

Figure 15. Time history curves of three-direction displacement of 30° pipe

Table 10. A1-A4 artificial wave seismic analysis data

| Number | Time/s | Max stress | Max strain | Max displacement |
|--------|--------|------------|------------|-----------------|
| A1     | 8.32   | 60.6       | 0.000294   | 0.7561          |
| A2     | 5.58   | 172        | 0.000937   | 12.536          |
| A3     | 3.22   | 256        | 0.001112   | 15.31           |
| A4     | 4.2    | 341        | 0.0023     | 16.53           |

Table 11. B1-B4 Artificial wave seismic analysis data

| Number | Time/s | Max stress | Max strain | Max displacement |
|--------|--------|------------|------------|-----------------|
| B1     | 4.2    | 29.75      | 0.000133   | 0.49            |
| B2     | 4.08   | 188        | 0.001003   | 8.887           |
| B3     | 3.14   | 265        | 0.001265   | 10.658          |
| B4     | 3.02   | 351        | 0.001648   | 20.665          |

Table 12. C1-C4 Artificial wave seismic analysis data

| Number | Time/s | Max stress | Max strain | Max displacement |
|--------|--------|------------|------------|-----------------|
| C1     | 4.88   | 48.78      | 0.000225   | 1.005           |
| C2     | 10.12  | 200        | 0.000668   | 8.863           |
| C3     | 13.56  | 243        | 0.000923   | 10.873          |
| C4     | 10     | 255        | 0.00113    | 11.575          |
Table 13: D1-D4 Artificial wave seismic analysis data

| Number | Time/s | Max stress | Max strain | Max displacement |
|--------|--------|------------|------------|------------------|
| D1     | 5.52   | 45         | 0.000202   | 0.986            |
| D2     | 10.28  | 198        | 0.000448   | 6.852            |
| D3     | 12.42  | 256        | 0.000668   | 11.217           |
| D4     | 13.22  | 268        | 0.000786   | 16.44            |

Table 14: E1-E4 Artificial wave seismic analysis data

| Number | Time/s | Max stress/Mpa | Max strain | Max displacement/cm |
|--------|--------|----------------|------------|---------------------|
| E1     | 9.22   | 35.5           | 0.00017    | 0.88                |
| E2     | 5.54   | 215            | 0.00067    | 5.524               |
| E3     | 8.88   | 246            | 0.00088    | 8.667               |
| E4     | 10.22  | 266            | 0.00105    | 19                  |

From Figure 5 to Figure 15, it can be seen that the pipeline span form is the same, and the displacement deformation of different pipeline span lengths is consistent regardless of el-Centro wave or artificial wave action. The time-history shape of the structure's X-direction displacement is basically consistent with that of the seismic wave, with the same number of peaks and troughs. However, the Y-direction and Z-direction displacement are not consistent with the seismic wave, and the displacement of different pipeline spans varies greatly. The y-direction and Z-direction displacements of various spanning forms of pipelines no longer converge when the span length exceeds 20m, resulting in structural failure.

As the yield limit of ordinary carbon steel is 216-235mpa, the strength limit is 373-461mpa. The maximum tensile strain is 0.01, and the compressive strain is 0.022. According to table 5 to Table 14, the damage of each model can be seen, as shown in Table 15.

Table 15: Breakage of each model

| Broken case | The whole structure loses its bearing capacity | Plastic deformation but the whole structure is not destroyed | No damage occurred |
|-------------|-----------------------------------------------|----------------------------------------------------------|-------------------|
| The model number | A3, A4, B3, B4, C3, C4, D3, D4, E3, E4 | C2, D2, E2 | A1, A2, B1, B2, C1, D1, E1 |

In conclusion, when the pipeline span form is certain, the pipeline span length should be reasonably selected, and the pipeline that spans more than 20 meters will be in a dangerous failure state.

3.4. Influence of pipeline crossing Form on pipeline under el-Centro wave action

When the span length of pipeline is fixed, the data such as the maximum stress of each model of different pipeline spanning form under the action of el-Centro wave earthquake are summarized in Table 16-19.

Table 16: Seismic analysis data of 15m model

| Number | Time/s | Max stress | Max strain | Max displacement |
|--------|--------|------------|------------|------------------|
| A1     | 4.84   | 66         | 0.00032    | 0.755            |
| B1     | 4.5    | 33.2       | 0.000158   | 0.58             |
Table 17. Seismic analysis data of 20m model

| Number | Time/s | Max stress | Max strain | Max displacement |
|--------|--------|------------|------------|-----------------|
| A2     | 12     | 190        | 0.001167   | 8.384           |
| B2     | 5.02   | 193        | 0.001014   | 9.785           |
| C2     | 12.04  | 220        | 0.000774   | 11.246          |
| D2     | 11.86  | 213        | 0.000538   | 7.995           |
| E2     | 5.66   | 220        | 0.000732   | 6.324           |

Table 18. Seismic analysis data of 25m model

| Number | Time/s | Max stress | Max strain | Max displacement |
|--------|--------|------------|------------|-----------------|
| A3     | 12.4   | 274        | 0.001332   | 13.305          |
| B3     | 5.04   | 267        | 0.001362   | 11.325          |
| C3     | 14.64  | 257        | 0.001023   | 11.221          |
| D3     | 14.62  | 260        | 0.000763   | 13.247          |
| E3     | 8.62   | 252        | 0.000867   | 9.956           |

Table 19. Seismic analysis data of 30m model

| Number | Time/s | Max stress | Max strain | Max displacement |
|--------|--------|------------|------------|-----------------|
| A4     | 13.7   | 312        | 0.0015     | 14.5            |
| B4     | 11.38  | 368        | 0.001753   | 22.735          |
| C4     | 12     | 261        | 0.00135    | 12.6            |
| D4     | 14     | 278        | 0.000845   | 18.954          |
| E4     | 10.06  | 287        | 0.001369   | 21              |

3.5. Influence of pipeline crossing Form on pipeline under artificial wave action

When the span length of pipeline is fixed, the obtained maximum stress and other data of various models of pipeline spanning form under the action of artificial wave earthquake are summarized in Table 20-23.

Table 20. Artificial wave seismic analysis data of 15m model

| Number | Time/s | Max stress | Max strain | Max displacement |
|--------|--------|------------|------------|-----------------|
| A1     | 8.32   | 60.6       | 0.000294   | 0.7561          |
| B1     | 4.2    | 29.75      | 0.000133   | 0.49            |
From Table 16 to Table 23, it can be seen that the pipeline span length is the same, and the seismic performance is related to the pipeline span form under the action of el-Centro wave or artificial wave. The data in the analysis table show that : (1) all the spanning pipelines have good seismic capability when the span length is 15 meters, and the 90° pipeline has the best seismic capability at this time. (2) When the spanning length of pipelines of 60° and 30° is 20 meters, plastic deformation may occur due to yield. The seismic resistance of other spanning forms is straight pipe, 90° and 45° from strong to weak. (3) All pipeline spanning forms are damaged when the span length exceeds 20 meters, and have no seismic capability.
4. Conclusion

Through the numerical simulation analysis, it is found that the maximum stress occurs in the middle part of the pipeline span. Under the condition of a certain pipe diameter:

(1) When the spanning form of the pipeline is consistent, the seismic performance of the structure decreases with the increase of the span length, and the maximum stress of the structure increases. The increase amplitude is first urgent and then alleviated. When the span length of the pipeline exceeds 20 meters, the pipeline fails.

(2) When the span length of pipelines is consistent, the seismic performance of straight pipelines is the best. When the span length of pipeline is more than 20 meters, it is risky to adopt the self-span scheme of pipeline, and other span forms such as truss pipeline span and suspension pipeline span should be considered based on the actual situation.

References:

[1] Guo H, Wu S. (1995) Finite element analysis of bending vibration of infusion pipe under vertical seismic load[J]. Journal of Vibration Engineering, 8(4): 84-388

[2] Chen Z, Li J et al. (1996) Seismic reliability analysis of above-ground pipelines[J]. Industrial building, 26(22): 1-8

[3] Karamitros D K, Bouckovalas G D et al. (2006) Stress analysis of buried steel pipelines at strike-slip fault crossings[J]. Soil Dynamics and Earthquake Engineering, 27:200-211.

[4] Newmark N M, Hall W J. (1975) Pipeline design to resist large fault displacement[C]. Proceedings of US Conference on Earthquake Engineering, Ann Arbor, Michigan: 416-425.

[5] Ma Y. Study on wind resistance and seismic resistance of beam type cross water conveyance pipeline[D]. Xi'an: Chang'an University, 2007