ISSN: 2664-9640

Contrast analysis of the stability of various top-cover structure based on workbench

Xing Zou [1,2], Wei Li [2,a,*], Lang Deng [1,2], Chengxu Shu [1,2], Shaojiu Jiang [1,2]

[1]School of Mechanical and Electrical Engineering, Southwest Petroleum University, Chengdu, Sichuan, 610500, China;

[2]KeyLaboratory of Oil and Gas Equipment Ministry of Education, Southwest Petroleum University, Chengdu, Sichuan, 610500, China.

[a]82867973@qq.com

Abstract

In this paper, a cap-and-cap depressurization mining method for surface and shallow non-forming rock gas hydrate is proposed. Through theoretical analysis and numerical analysis of structural stability of different structure cap-and-cap devices, the critical buckling load values of different structure cap-and-cap devices are obtained, and the reliability of numerical solution is verified. At the same time, comparing the critical buckling value of each structure under different thickness, considering the variation trend with thickness, it is concluded that the critical buckling value of spherical Capping is most sensitive to the thickness variation, which can more meet the method of Capping depressurization mining, and provide a reference for the structural design of subsequent Capping devices.

Keywords

Hydrate mining; Top-Cover Subpressure Method; pressure-resistant thin shell; stability analysis.

1. Introduction

As a new energy source, natural gas hydrate not only has large reserves, clean and pollution-free, but also has the characteristics of shallow buried, weak cementation and poor stability in the surface layer and shallow layer of non-formed rock natural gas hydrate, which will cause the decomposition, gasification and release of natural gas hydrate due to the change of temperature and pressure conditions in the area. Compared with the diagenetic natural gas hydrate in the deep seabed, it is easier to be exploited[1-2].At present, the methods for exploitation of shallow and surface non-forming rock natural gas hydrate are mainly depressurization, carbon dioxide displacement, thermal injection, injection chemical inhibitor and solid fluidization[3-4]. This article mainly focuses on the depressurization mining method, using the method of capping and depressurization to realize the mining of non-diagenetic gas hydrates in the shallow and surface layers of the seabed. Considering the economic benefits of commercial mining, however, the capping device needs to reach a certain size to meet the production requirements. But the giant capping device will suffer a large negative pressure load during the mining process, and there will be different instability conditions with different shapes, thickness and reinforcement methods.

Comparing the stability of the hemisphere, semi-ellipsoid, half-egg-shaped body and capping devices with different thicknesses under the same shape. Then the workbench finite element analysis software was used to calculate the critical buckling load and buckling modes of different structures. Finally, through the comparison of the results, a structure that is more suitable for the construction of the capping device for submarine surface and shallow non-

ISSN: 2664-9640

lithogenic gas hydrate mining is finally obtained, which provides a reference for the design of the subsequent capping device structure.

2. Mathematical model of different top-cover structures

According to the geometric characteristics of different structures, the spherical cover top belongs to the center symmetric rotary thin shell structure, while the ellipsoidal cover top and the egg-shaped cover top belong to the axis symmetric rotary thin shell structure. The bus equation of the egg-shaped cover top[5] is as follows.

Egg-shaped cover top bus equation:

$$\frac{x^2}{a^2} \times \frac{y^2}{(b + x \cdot \tan\theta)^2} = 1 \tag{1}$$

Through deformation:

$$y = \pm \frac{b + x\tan\theta}{a}\sqrt{(a^2 - x^2)} \tag{2}$$

where a is the radius of the long axis of the top cover; b is the radius of the short axis of the top cover; θ is the egg-shaped angle; e is the centrifugal distance of the top cover; x and y are the points on the curve.

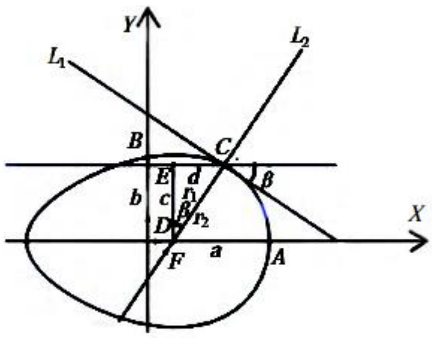


Fig.1 Egg-shaped shell curve

First-order derivative function (3) and second-order derivative function (4) can be obtained respectively by first-order derivative and second-order derivative of the upper bus equation (2):

$$y' = \frac{-2x^2\tan\theta - bx + a^2\tan\theta}{a\sqrt{(a^2 - x^2)}} \tag{3}$$

$$y'' = \frac{-3a^2x\tan\theta + 2x^3\tan\theta - a^2b}{a\,(a^2 - x^2)^{3/2}} \tag{4}$$

In order to obtain the first curvature and the second curvature equation of the egg-shaped shell, the first curvature equation can be calculated by the arc differential equation[6] as:

$$r_1 = \left|\frac{[1 + (y'c)^{3/2}]}{y''}\right| \tag{5}$$

And the second curvature equation[6] is obtained from the hook theorem:

$$r_2 = \sqrt{(d^2 + y^2)} \tag{6}$$

Egg-shaped cap coefficient formula and volume formula [7] are respectively:

$$\frac{\partial\rho}{\partial t}+\nabla\bullet(\rho\dot{V})=0 \tag{4-1}$$

$$S_1 = b/a \tag{7}$$

$$V_{蛋}=(\frac{a+b}{2}+e)\cdot\pi b^2 \tag{8}$$

3. Critical buckling load of different top-cover structures

For thin-walled shell structures, buckling failure is the most common failure form.At home and abroad, the concept of structural safety was first proposed by Eudenthal in 1945, and the research on structural stability has been until now [8]. For the pressure-resistant shell, the stability research is a hot topic in the structural research [9]. After decades of development, theoretical calculation formulas of various shell structures have been derived successively, which is of great help to the study of shell stability.

3.1. Critical buckling load of spherical top cover

For the development of structural stability of theoretical spherical shells, the critical buckling load[10] of under uniform pressure load[10] is expressed as:

$$P_{cr}=\frac{2E}{\sqrt{3(1-\mu^2)}}(\frac{t}{R_c})^2\approx 1.21Et^2/R_c^{\ 2} \tag{9}$$

Where P_{cr} is the theoretical critical pressure of the spherical shell, t is the thickness of the spherical shell, R_c is the radius of the curved surface in the spherical shell, E is the elastic modulus of the material, and μ is the Poisson's ratio of the material.

3.2. Critical buckling load on oval top cover

Critical buckling load formula of ellipsoidal shell can be obtained according to Liao Qirui and others' translation of the Soviet literature "Design of Thin-Walled Structures ". In this paper, the stability of a flat ellipsoidal container under internal compression is deduced based on the momentless theory. The theoretical critical buckling load formula for buckling is obtained[10-13]. The formula (10) is modified as follows:

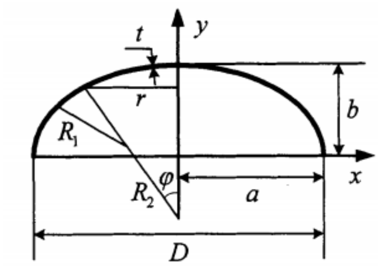


Fig.2 Schematic diagram of ellipsoid

$$P_{cr}=\frac{8E}{(\frac{D}{t})^2\cdot\left|1-2(\frac{1}{m})^2\right|\cdot\sqrt{3(1-\mu^2)}}\cdot K \tag{10}$$

Where E is the Young's modulus; the correction coefficient K =0.56; D is the length of the long axis; t is the shell thickness; m is the modulus, i.e. the ratio of the long axis to the short axis; μ is the Poisson's ratio.

3.3. Critical buckling load of egg-shaped top cover

An egg-shaped pressure-resistant shell is a special-shaped pressure-resistant shell whose buckling critical load qcr can be calculated by the Mushtri equation[14-17] as follows:

$$P_{cr}=\frac{2Et^2}{(2\bar{r}_1-\bar{r}_2)\cdot\bar{r}_2}\cdot\frac{1}{\sqrt{3(1-\mu^2)}} \tag{11}$$

An egg-shaped pressure-resistant shell is a special-shaped pressure-resistant shell whose buckling critical load qcr can be calculated by the Mushtri equation[14-17] as follows:

$$\begin{cases}\bar{r}_1=\frac{1}{2a}\int_{-a}^{a} r_1 dx\\ \bar{r}_2=\frac{1}{2a}\int_{-a}^{a} r_2 dx\end{cases} \tag{12}$$

Where E is the modulus of elasticity; t is the thickness of the shell; the mean value of the first radius of curvature and the second radius of curvature of the egg shell; μ is the Poisson's ratio of the material.

4. Numerical analysis of stability of different top cover

4.1. Establishment of top-cover model

Considering the processing difficulty and simplified calculation of the large-scale Capping, and reducing the influence of the processing and assembly process on the results, the following assumptions are made for the Capping model:(1) the overall model of the Capping is formed by splicing the shell plates and connected by welding, so it can be considered as a whole model;(2) the structural changes of part of the area caused by welding are not considered, the surface of the Capping model is smooth, and the shell plates are perfectly connected;(3) the thickness of each part of each shell plate is consistent;(4) the skirt structure inserted below the seabed mud bed is not considered, only the upper half shell structure is modeled.

4.2. Parameter setting

In this paper, the buckling problem of a variety of structural capping devices is analyzed and calculated by the workbench finite element analysis software.In consideration of the commercial value of natural gas hydrate exploitation, the size of capping devices is much larger than that of ordinary shells.In order to ensure the reliability of the calculation results, it is necessary to define the model size, parameters, boundary condition constraints and external loads.

(1) The top model size is based on the spherical top with a radius of 5m. Other dimension parameters are estimated under the premise of ensuring approximate volume and the same coverage area. See Table 1 below for specific parameters. The top steel is 10Ni steel, whose material parameters are: material density =7850 kg/m3, Poisson's ratio =0.3, elastic modulus E=210 GPa, and minimum yield strength of casing is 520MPa.

(2) In order to simplify the calculation, the skirt structure inserted below the seabed mud bed is not considered in the model, which is simplified as a complete constraint to the bottom boundary of the top half shell.

(3) The external static pressure load and the internal static pressure load are 30.1MPa and 30MPa respectively (considering that the smaller thickness of the cover can not bear the larger pressure, the 0.1MPa pressure difference can avoid the load exceeding the buckling strength limit of the cover and ensure the correctness of the calculation results of the small thickness of the cover), and the seabed temperature is 6-7°C.

ISSN: 2664-9640

4.3. Grid division and optimization

The half-shell model is divided into three kinds of top-cover models based on SHELL181 shell unit, which are divided into hexahedron and tetrahedron mixed mesh.The methods of tetrahedron and hexahedron mesh division are basically the same.However, hexahedron mesh has obvious advantages in human intervention, calculation accuracy, mesh number and mesh division times.At the same time, considering the curved surface structure of the top cover, tetrahedron mesh can improve the quality of mesh division and ensure the correctness of the calculation results.

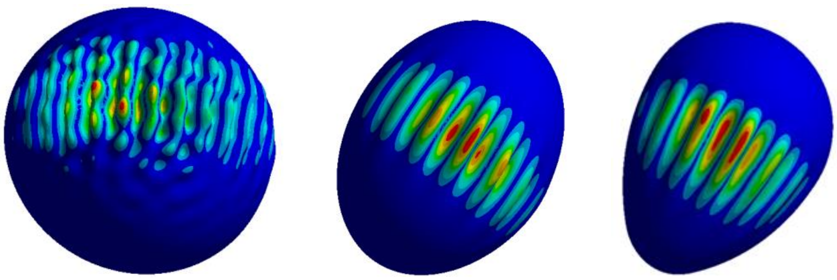
5. Conclusion and discussion

5.1. Comparison of numerical analysis results of variable thickness stability of different top-cover structures

In order to obtain the analysis results of the change of the cover top with the thickness of different structures, and considering the pressure bearing performance of the cover top, the thickness of the cover top shell was increased by 50% with the minimum thickness of 10mm.The analysis result of buckling critical load on that top of each structure under different thickness is shown in Table 1.

Table 1 Numerical results of stability analysis of Capping with thickness

Category	Spherical cap		Ellipsoid cap		Egg cap	
	Modal	Buckling critical Load/MPa	Modal	Buckling critical Load/MPa	Modal	Buckling critical Load/MPa
10	38	0.85	15	0.409	8	0.80
11	36	1.052	14	0.515	7	0.86
12	35	1.273	13	0.632	7	0.92
13	33	1.514	13	0.759	6	0.95
14	32	1.773	13	0.896	5	0.99
15	31	2.051	6	1.67	5	1.18



a. Spherical cap b. ellipsoid cap c. egg cap

Fig.3 The simulation results of each structure

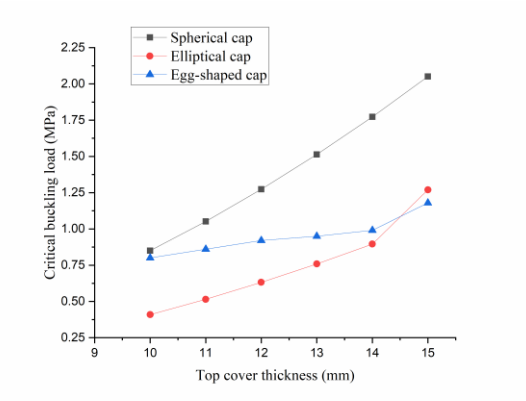


Fig.4 Variation of critical buckling load of various structures with thickness

According to the above analysis results, the buckling critical load of each structure top mainly occurs at the waist, and the buckling critical load rises with the increase of the shell thickness of the top; however, the buckling critical load of each structure top varies with the increase of the thickness, among which the spherical top has the most obvious change, indicating that the spherical top has stronger stability under the condition of thickness.

5.2. Comparative analysis of theoretical solutions and numerical solutions for different structures

According to the calculation formula and corresponding parameters of theoretical critical load of different structures, the theoretical critical load of different thickness of different structures can be solved. The results are shown in Table 2 below.

Table 2 Theoretical Critical Loads for Different Structures at Different Thicknesses

Category	Theoretical critical load / MPa		
	Spherical cap	Ellipsoid cap	Egg cap
10	0.968	1.269	0.882
11	1.171	1.322	0.939
12	1.426	1.468	0.995
13	1.636	1.584	1.024
14	1.897	1.679	1.061
15	2.103	1.829	1.249

By comparing the numerical solutions with the theoretical solutions, it is found that:(1) with the increase of thickness, the theoretical solutions of different structures are consistent with the numerical solutions, and the critical buckling load tends to increase with the thickness, which is consistent with the actual situation;(2) the theoretical solutions of spherical and egg-shaped Cappings are smaller than the numerical solutions of the same thickness, while the theoretical solutions of ellipsoidal and egg-shaped Cappings are larger than the numerical solutions of the same thickness;(3) although the theoretical solutions and numerical solutions have errors, but keep within the error range of 15%, and gradually decrease with the increase of thickness.

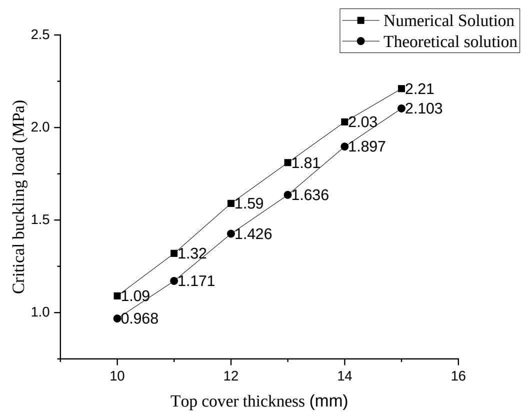


Fig.6 Variation of critical buckling load with thickness of spherical cap

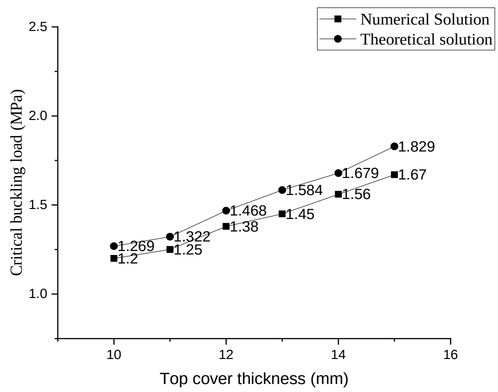


Fig.7 Variation of Critical Buckling Load of Ellipsoid Cap with Thickness

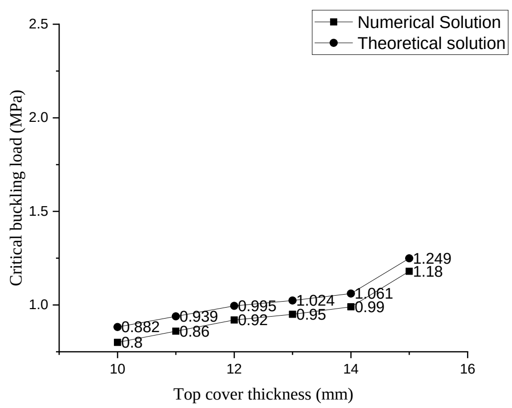


Fig.8 The Critical Buckling Load of Egg-shaped Top Cover Varies with Thickness

6. Conclusion

Based on the workbench finite element analysis software, the structural stability analysis of three different structures of half shells used as the top cover is carried out, and the numerical solution of the critical buckling load of different structures under different thickness is obtained. By comparing with the theoretical value of the critical buckling load, the correctness of the model is verified, and the comparison of the results of different thickness and different structure analysis provides a reference for the selection of the structure of the top cover for depressurization mining of natural gas hydrate top cover.The specific conclusions are as follows:

ISSN: 2664-9640

(1) Through numerical analysis and theoretical analysis, the bearing strength of shell structure with different shape is calculated, and the error is within acceptable range, and the reliability of numerical analysis results based on workbench shell structure is verified.

(2) The critical buckling load of three kinds of Capping structures (spherical, ellipsoidal and egg-shaped) will increase with the increase of thickness, but the increase amplitude varies greatly, among which the spherical Capping is the most obvious, the ellipsoidal Capping is the second, and the egg-shaped Capping is the smallest.

(3) In order to meet the commercial exploitation conditions of natural gas hydrate, the capping should bear as much pressure as possible to meet the pressure regulation and production requirements. Therefore, the spherical capping is more suitable for the depressurization exploitation conditions of natural gas hydrate capping.

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