Study on the Effect of Cement Sheath on the Stress of Gas Storage Well

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Abstract. Compressed natural gas (CNG) has been widely used as an automotive fuel in China, which the service security of CNG storage well (CSW), the main storage equipment in Chinese filling station, is becoming more and more prominent. In order to analyze the stress of CSW and its influencing factors, the mechanical model of CSW + cement sheath + stratum (CCS) processed by both elastic mechanics and finite element method was studied in this work. Using the most common well of $\Phi 177.8 \times 10.36$ mm as a calculation case to obtain the analytic solutions and numerical solutions of CCS. The results indicated that the analytic solutions and numerical solutions are very close with relative deviation less than 3%, which verified their reliability each other. The calculation case can prove that the stress of CSW reduced evidently due to the effect of well cementation, which equivalent to the value of circular and axial stress of CSW strengthens to 18% and 20%. And when increasing the elastic modulus of cement sheath, the stress of CSW decreased that the support and potentiation to CSW by cement sheath becomes stronger.

Keywords: CNG, Storage well, Cement Sheath, Stratum, Stress

1. Introduction
As pollution issues threaten the widespread use of fossil fuels, compressed natural gas (CNG) has been widely used as an automobile fuel instead of gasoline (petrol) and diesel [1-2]. CNG storage well (CSW), a new and economical way to storage CNG, has a lot of advantages, namely low cost, high reliability, easy operation, long lifetime, less area occupied, fast filling, large storage capacity, etc [3-4]. At present, the number of Chinese CNG filling stations are increasing rapidly. As far as the CSW is concerned, CSW accounts for 95\% of all the CNG filling station gas storage capacity in China [5].

Figure 1 shows that CSW is buried under the ground and surrounded by a cement sheath. High internal pressure is extruded and supported by both cement sheath and stratum, which CSW simultaneously bears internal and external pressure. Furthermore, CSW is commonly built in large cities with a dense population, which shall lead to major potential hidden danger, such as leakage, ignition, well-channeling, well-sinking even explosion [6-7]. Accordingly, this paper concerns to the stress analysis of CSW since the failure of the high pressure vessel can result in a fatal disaster.
2. Experimental Details

2.1. Elastic Mechanics Analysis
Considering the cement sheath and stratum, the mechanical model of CCS was counted as a multi-layer thick-walled cylinder of 3 kinds of materials on the basis of the elastic mechanics theory [8]. Before calculation, some necessary simplifications and assumptions are listed as follows:

1. The CSW is at the center of the well and owns uniform wall thickness;
2. The CCS belongs to line elastomer;
3. The consolidation between different materials is good without defect;
4. Stratum stress is well-proportioned.

The cross-sectional area of CSW is much smaller than the axial length, so that the axial deformation has constraints each other under the internal pressure and the strain components ($\varepsilon_x$, $\varepsilon_y$, $\varepsilon_{xy}$) paralleled to the cross section are not zero. Therefore, the mechanical model of CCS was analyzed under plane strain principle, as shown in figure 2 [9-10].

![Figure 1. Structure of CSW.](image1)
![Figure 2. Mechanical model of CCS.](image2)

where $r_1$ is internal radius of CSW, $r_2$ is external radius of CSW, $r_3$ is external radius of cement sheath, $r_4$ is external radius of stratum, $P_1$ is internal pressure of CSW, $P_4$ is external force from stratum, $P_2$ and $P_3$ represents the first and the second interfacial pressure.

2.2. Finite Element Analysis
To verify the accuracy of elastic mechanics analysis, the finite element method was applied for establishing the mechanical model of CCS by ANSYS software. Meanwhile, the finite element method requires some necessary data, such as dimensions, material performance, force and constraint of CCS. There are four steps for numerical calculation, including 3D model establishing, mesh generation, boundary conditions loading (including displacement and force) and finite element calculation [11-12]. For numerical efficiency, the 1/4 model was used for finite element analysis due to its symmetry.

3. Results

3.1. Parameters of an Example
The most common CSW of $\Phi 177.8\times 10.36$ mm with N80Q steel was taken as an instance to calculate both its analytic and numerical solutions. All the parameters required were shown in tables 1-3. The
internal pressure $P_1$ is the biggest operation pressure of CSW in Table 1. The external pressure $P_4$ is static pressure of underground liquid column of 150 m length of CSW in Table 3.

Table 1. Parameters for analytic and numerical calculation of CSW.

| Parameters | Yield Strength $\sigma_s$(MPa) | Tensile Strength $\sigma_b$(MPa) | Elasticity Modulus $E_1$(MPa) | Poisson's Ratio $\mu_1$ | Internal Radius $r_1$(mm) | External Radius $r_2$(mm) | Internal Pressure $P_i$(MPa) |
|------------|--------------------------------|--------------------------------|-------------------------------|------------------------|--------------------------|--------------------------|-----------------------------|
| CSW        | 552                            | 689                            | 206                           | 0.3                    | 78.54                    | 88.90                    | 25                          |

Table 2. Parameters for analytic and numerical calculation of cement sheath.

| Parameters | Elasticity Modulus $E_2$(MPa) | Poisson's Ratio $\mu_2$ | Internal Radius $r_2$(mm) | External Radius $r_3$(mm) |
|------------|--------------------------------|------------------------|---------------------------|--------------------------|
| Cement sheath | 7                                | 0.23                   | 88.90                     | 120.5                    |

Table 3. Parameters for analytic and numerical calculation of stratum.

| Parameters | Elasticity Modulus $E_3$(MPa) | Poisson's Ratio $\mu_3$ | Internal Radius $r_3$(mm) | External Radius $r_4$(mm) | External Pressure $P_4$(MPa) |
|------------|--------------------------------|------------------------|---------------------------|--------------------------|-----------------------------|
| Stratum    | 3                                | 0.2                    | 120.5                     | 602.5                    | 2                           |

3.2. Analytic Solution

Displacement equations of single-layer thick-walled cylinder were listed as follows [13-14], including external wall radial displacement of CSW $u_{11}$, internal wall radial displacement of cement sheath $u_{12}$, external wall radial displacement of cement sheath $u_{21}$, and internal wall radial displacement of stratum $u_{22}$:

$$u_{11} = \frac{r_3^2 r_1 (2 - \mu_1)}{E_1 (r_2^2 - r_1^2)} P_1 - \frac{r_3^2 (1 - 2 \mu_1) + (1 + \mu_1) r_3^2 r_2}{E_1 (r_2^2 - r_3^2)} P_2 = f_1 P_1 - f_2 P_2$$

(1)

$$u_{12} = \frac{r_2^2 (1 - 2 \mu_1)}{E_2 (r_3^2 - r_2^2)} P_2 - \frac{r_2^2 r_3 (2 - \mu_2)}{E_2 (r_3^2 - r_2^2)} P_3 = f_3 P_2 - f_4 P_3$$

(2)

$$u_{21} = \frac{r_3^2 r_2 (2 - \mu_2)}{E_3 (r_4^2 - r_2^2)} P_2 - \frac{r_3^2 (1 - 2 \mu_2) + (1 + \mu_2) r_3^2 r_3}{E_3 (r_4^2 - r_3^2)} P_4 = f_5 P_2 - f_6 P_3$$

(3)

$$u_{22} = \frac{r_4^2 (1 - 2 \mu_3) + (1 + \mu_3) r_4^2 r_4}{E_4 (r_4^2 - r_2^2)} P_4 - \frac{r_4^2 r_3 (2 - \mu_3)}{E_4 (r_4^2 - r_3^2)} P_4 = f_7 P_3 - f_8 P_4$$

(4)

The radial displacement of the first and the second interfacial were equal in terms of the model of CCS was continuous as shown in Eq. 5:

$$\begin{align*}
    f_1 p_1 - f_2 p_2 &= f_3 p_2 - f_4 p_3 \\
    f_5 p_2 - f_6 p_3 &= f_7 p_3 - f_8 p_4 \\
\end{align*}$$

(5)

where $f_1$-$f_8$ are assumptive calculated coefficient. The first and the second interfacial pressure $p_2$ and $p_3$ were calculated by the Eq. 5, as shown in Eq. 6.
\[
\begin{aligned}
\begin{cases}
P_2 &= \frac{f_1 p_1 (f_6 + f_7) + f_3 f_4 p_4}{(f_2 + f_3) (f_6 + f_7) - f_4 f_5} \\
P_3 &= \frac{f_5 p_4 (f_2 + f_3) + f_4 f_5 p_1}{(f_2 + f_3) (f_6 + f_7) - f_4 f_5}
\end{cases}
\end{aligned}
\]  \hspace{1cm} (6)

The radial stress \( \sigma_r \), circular stress \( \sigma_\theta \) and axial stress \( \sigma_z \) equations of CCS were obtained due to single-layer thick-walled cylinder stress equation, as shown in Eqs. 7-9 [12].

For CSW \((r_1 < r < r_2)\),

\[
\begin{aligned}
\sigma_{1r} &= \frac{r_1^2 r_2^2}{r_2^2 - r_1^2} \frac{p_2 - p_1}{r^2} + \frac{r_2^2 p_1 - r_1^2 p_2}{r_2^2 - r_1^2} \\
\sigma_{1\theta} &= -\frac{r_1^2 r_2^2}{r_2^2 - r_1^2} \frac{p_2 - p_1}{r^2} + \frac{r_1^2 p_1 - r_2^2 p_2}{r_2^2 - r_1^2} \\
\sigma_{1z} &= 2\mu_1 \frac{r_1^2 p_1 - r_2^2 p_2}{r_2^2 - r_1^2}
\end{aligned}
\]  \hspace{1cm} (7)

For cement sheath \((r_2 < r < r_3)\),

\[
\begin{aligned}
\sigma_{2r} &= \frac{r_2^2 r_3^2}{r_3^2 - r_2^2} \frac{p_3 - p_2}{r^2} + \frac{r_2^2 p_2 - r_3^2 p_3}{r_3^2 - r_2^2} \\
\sigma_{2\theta} &= -\frac{r_2^2 r_3^2}{r_3^2 - r_2^2} \frac{p_3 - p_2}{r^2} + \frac{r_3^2 p_2 - r_2^2 p_3}{r_3^2 - r_2^2} \\
\sigma_{2z} &= 2\mu_2 \frac{r_2^2 p_2 - r_3^2 p_3}{r_3^2 - r_2^2}
\end{aligned}
\]  \hspace{1cm} (8)

For stratum \((r_3 < r < r_4)\),

\[
\begin{aligned}
\sigma_{3r} &= \frac{r_3^2 r_4^2}{r_4^2 - r_3^2} \frac{p_4 - p_3}{r^2} + \frac{r_3^2 p_3 - r_4^2 p_4}{r_4^2 - r_3^2} \\
\sigma_{3\theta} &= -\frac{r_3^2 r_4^2}{r_4^2 - r_3^2} \frac{p_4 - p_3}{r^2} + \frac{r_4^2 p_3 - r_3^2 p_4}{r_4^2 - r_3^2} \\
\sigma_{3z} &= 2\mu_3 \frac{r_3^2 p_3 - r_4^2 p_4}{r_4^2 - r_3^2}
\end{aligned}
\]  \hspace{1cm} (9)

The stress analytic solutions of any point of CCS could be obtained by Eqs. 7-9. The stress analytic solutions of the above example were calculated, as shown in table 4.

**Table 4. Stress analytic solutions of CSW.**

| Stress                  | Circular stress of internal wall (MPa) | Circular stress of external wall (MPa) | Axial stress (MPa) |
|-------------------------|----------------------------------------|---------------------------------------|-------------------|
| Analytic solutions      | 151.32                                  | 131.97                                 | 37.90             |

3.3. Numerical Solution

The 1/4 finite element model of the above example was studied. The model was divided into hexahedron eight-node element with the characteristics of plasticity, stress strengthening, expansion,
creep, large strain and large deformation, and possessed three directions of degrees-of-freedom as shown in figure 3. Then the internal wall of CSW was loaded with the internal pressure of 25MPa ($P_1$) from CNG and the external wall of cement sheath was loaded with external pressure of 2MPa ($P_2$) from stratum. Ultimately, based on the fourth strength theory, the Mises equivalent stress distribution of CCS was obtained by ANSYS calculation, as shown in figure 4, where the maximal Mises equivalent stress was 170.22MPa. In addition, using ANSYS postprocessor, the circular and axial stress were obtained, which indicated the maximal stress of CCS occurred in the internal wall of CSW, as shown in table 5, while the stress of cement sheath and stratum were much lower than CSW.

![Finite element model and mesh generation of CCS.](image1)

![Stress distribution of CCS.](image2)

**Table 5. Stress numerical solutions of CSW.**

| Stress                  | Circular stress of internal wall (MPa) | Circular stress of external wall (MPa) | Axial stress (MPa) |
|-------------------------|----------------------------------------|---------------------------------------|--------------------|
| Numerical solutions     | 148.14                                 | 128.28                                | 37.03              |

**4. Discussion**

The results of analytic calculation and numerical calculation were very close and their relative deviation was less than 3%, which verified their reliability. In addition, based on the national standard of GB150-2011, the safety factor of tensile strength ($n_b$) is 2.6 and the safety factor of yield strength ($n_s$) is 1.5, therefore the admissible stress ($[\sigma]$) of N80Q steel was:

$$[\sigma] = \min \left( \frac{\sigma_s}{n_s}, \frac{\sigma_b}{n_b} \right) = \min \left( \frac{552}{1.5}, \frac{689}{2.6} \right) = 265 \text{ MPa}$$ (10)

The admissible stress (265 MPa) was higher than the practical value of CSW (170.22 MPa), indicating that CSW was still in elastic and secured state.

The results of the stress analysis and calculation for CCS indicated that the well cementation could transmit the compression of crustal stress to CSW, and prevented the deformation of CSW at the same time. To analyze the potentiation of well cementation, the circular and axial stress of CSW internal wall before well cementation was calculated, which was 184.58 MPa and 47.87 MPa respectively by Eq. 7. Based on the Eq. 11, the potentiation factor by well cementation to CSW circular and axial stress was 18% and 20%, respectively.

$$\delta = \frac{\sigma' - \sigma}{\sigma'}$$ (11)

where $\sigma'$ was the stress of CSW before well cementation and $\sigma$ was the stress of CSW after well cementation.

The pressure fluctuation was very high at CNG storage time and gas filling time, even beyond the operation pressure sometimes. To ensure the safety operation of CSW, its load capacity should be
enhanced. Compared to improving the material of CSW and the performance of stratum, changing the parameters of cement sheath was easier. This work chose the elasticity modulus of cement sheath between 3 GPa and 28 GPa to obtain the stress of CSW by Eq.7, as shown in table 6. It indicated that the stress of CSW decreased with the increase of elasticity modulus of cement sheath, while the support and potentiation to CSW by cement sheath became stronger for its rigidity helps CSW bear more load. For this reason, more and more scholars dedicated on the research to adjust the additive, water-cement ratio and grade of cement to improve well cementation technology for increasing its elasticity modulus.

Table 6. Circular stress of CSW with different elasticity modulus of cement sheath.

| Elasticity modulus of cement sheath (GPa) | The circular stress of internal wall (MPa) | The circular stress of external wall (MPa) |
|------------------------------------------|------------------------------------------|------------------------------------------|
| 3                                        | 163.28                                   | 143.04                                   |
| 9                                        | 145.04                                   | 126.62                                   |
| 15                                       | 128.15                                   | 111.60                                   |
| 21                                       | 113.20                                   | 98.11                                    |
| 28                                       | 99.76                                    | 85.94                                    |

5. Summary
As for CSW, the stress not only comes from internal pressure but also extrusion force by stratum. The research on the stress distribution of CCS in light of a multi-layer thick-walled cylinder has been carried out in the present study. On the basis of the elastic mechanics theory and the finite element method of ANSYS, the analytic and numerical solutions of CSW have been obtained, which could calculate the stress at any point. The results indicate that well cementation could enhance the load capacity of CSW, and the potentiation factor by which to CSW circular and axial stress is 18% and 20%, respectively. The stress of CSW decreased with the increase of elasticity modulus of cement sheath. These finding can provide a way to improve the load capacity of CSW.

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