5th International Conference on Ocean Energy, 4-6 November, Halifax

THE BEHAVIOR OF OCAES VESSEL UNDER OPERATIONAL LOAD

J. Xiao[1], M. Gabr[1] and M. Rahman[1]

[1] Department of Civil, Construction and Environmental Engineering,
North Carolina State University,
2501 Stinson Drive, Campus Box 7908, Raleigh, NC 27695-7908, USA
Email: jxiao3@ncsu.edu

ABSTRACT

An Offshore Compressed Air Energy Storage (OCAES) approach is being considered as a solution to store intermittently generated energy from renewable sources. The operating mechanism is to submerge the storage vessel into the deep ocean, convert the energy into compressed air and store it using the hydrostatic water pressure to balance the compressed air pressure without requiring the storage vessels of high strength. An additional advantage is that the interface of air and water acts as a piston to seal the vessel and maintain the air pressure level.

In this study, a rectangular concrete tank and a concrete cylinder are investigated as the configuration of OCAES vessel. Characterization of the induced loading in this case is developed and the vessels' response under operational loading is investigated. The operational load is a time-dependent internal pressure induced by the air/water exchange in the inflation/deflation process. The stress distribution and deformation pattern in the OCAES vessel at different loading stages are studied by using the multi-physics FEM program COMSOL.

Keywords: Compressed Air storage, ocean energy, offshore vessel, OCAES

1. INTRODUCTION

The heightened interest in power generation from renewable sources includes the possibility of using offshore wind and waves on an industrial scale. Both wind and wave energy sources are intermittent in nature and depend on seasonal, tidal, and climatological factors. However, the electrical demand is not balanced throughout the day and power grids regulate the amount of power being supplied at all times. The imbalance in supply and demand has been addressed in the industry through the introduction of energy storage as a means for power leveling.

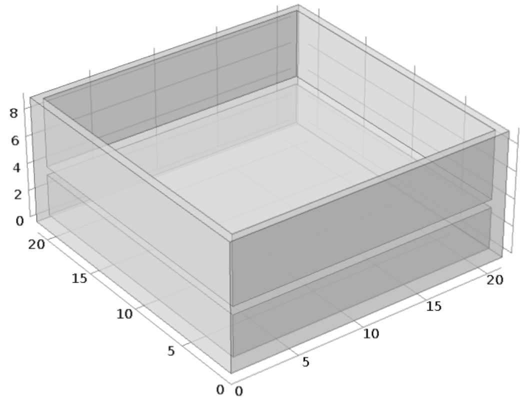
As an emerging technology of energy storage, the Offshore Compressed Air Energy Storage (OCAES) is developed from Compressed Air Energy Storage (CAES). The idea of CAES is to store the compressed air in the natural geological formations, such as salt domes, depleted oil and gas reservoirs, which can provide the necessary deformation and conductivity constraints. There are two operational on-land CAES plants (Crotogino et al. 2001). One is a 290 MW plant in Huntorf, Germany built in 1978. The other is a 110 MW plant located in Mclntosh, AL, which was built in 1991. Currently there are seven proposed CAES projects in the US in the states of Iowa, New York, California, Ohio, Montana, and Texas (2 projects)(Robb 2011).

OCAES is an innovative concept that is based on taking advantage of the hydrostatic water pressure to balance the compressed air pressure without requiring high-inner-pressure-resistant vessels. Two possible configurations for OCAES vessels have been proposed. One employs reinforce synthetic fabric air bags (Pimm et al. 2011; Garvey 2012). The second uses a rigid vessel (Seymour 2007). The rigid vessel has an air-water interface inside, while the flexible air bag can avoid the mixing of the air and water. However, compared with the synthetic fabric bag, the anchorage of the rigid vessel is more feasible in terms of safety for long-term operation.

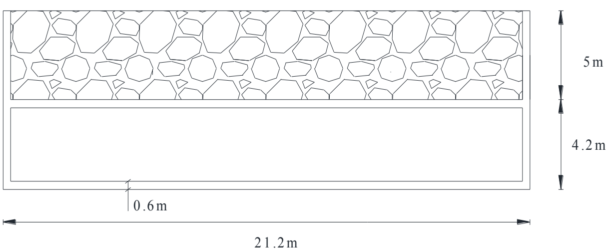
2. CONFIGURATIONS OF OCAES VESSEL

The first configuration of the storage vessel is a rectangular concrete tank with inner dimensions of 20 m × 20 m × 3 m, the wall thickness is 0.6 m, as shown in Figure 1. The ballast is applied on the top to anchor the vessel when it is full of air. Considering a safety factor greater than 1.3 (refer to the appendix A), the height of ballast is 5 m. The energy storage capacity is 12,400 MJ (refer to Appendix C).

The second configuration is a concrete cylinder with the diameter of 15 m, the height of 17 m (storage space) and wall thickness of 0.6 m, as shown in Figure 2. The storage volume is 2650 m^3 (refer to Appendix B). The corresponding energy storage capacity is 27,400 MJ (refer to Appendix C) equivalent to two rectangular vessels identified in the first configuration. In this case, suction caissons are used to anchor the system, providing that the geologic conditions are amenable to such a setup.

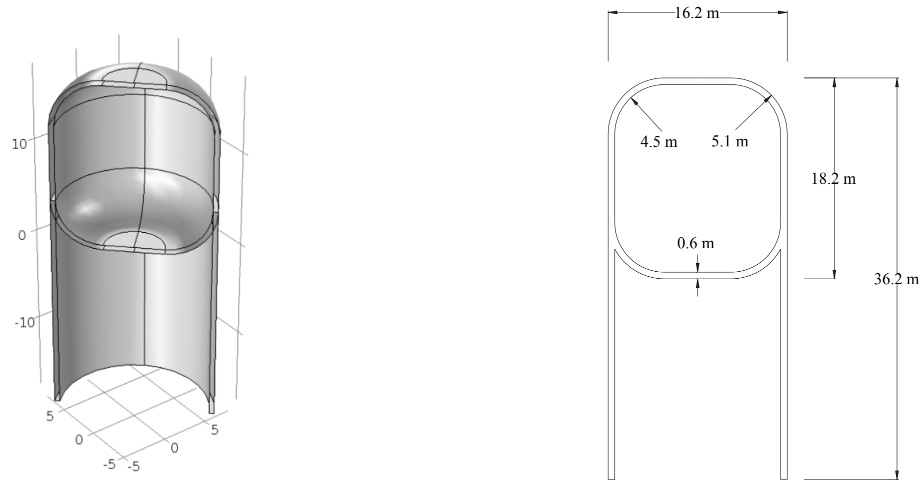


3D ISOMETRIC VIEW



CROSS SECTION

FIGURE 1. THE CONFIGURATION OF RECTANGULAR TANK



3D ISOMETRIC VIEW (CUT OPEN) CROSS SECTION

FIGURE 2. THE CONFIGURATION OF CYLINDRICAL VESSEL

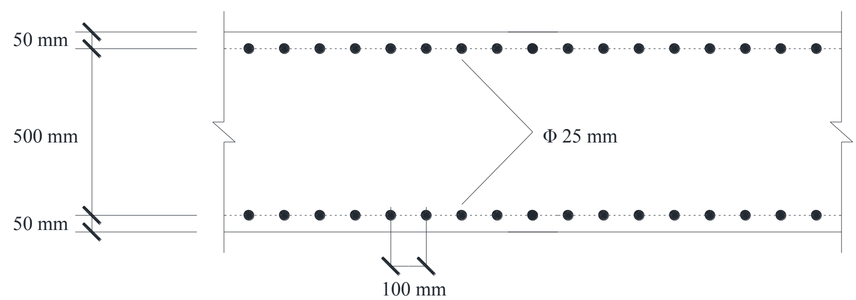


FIGURE 3. THE REINFORCEMENT LAYOUT IN THE WALL FOR BOTH CONFIGURATIONS

The material is reinforced concrete with properties listed in Table 1. The section of wall is shown in Figure 3. The thickness of the wall plate is 600 mm and the thickness of concrete protective layer is 50 mm. Both tensile reinforcement and compressive reinforcement are planned. The reinforcement is steel bar of 25 mm in diameter, the lateral distance between the adjacent reinforcement is 100 mm. The reinforcements are laid out in both directions in plane.

Material	Density (kg/m^3)	Young's Modulus (MPa)	Poisson's Ratio	Tensile Strength (MPa)
Concrete	2300	25,000	0.2	4~6

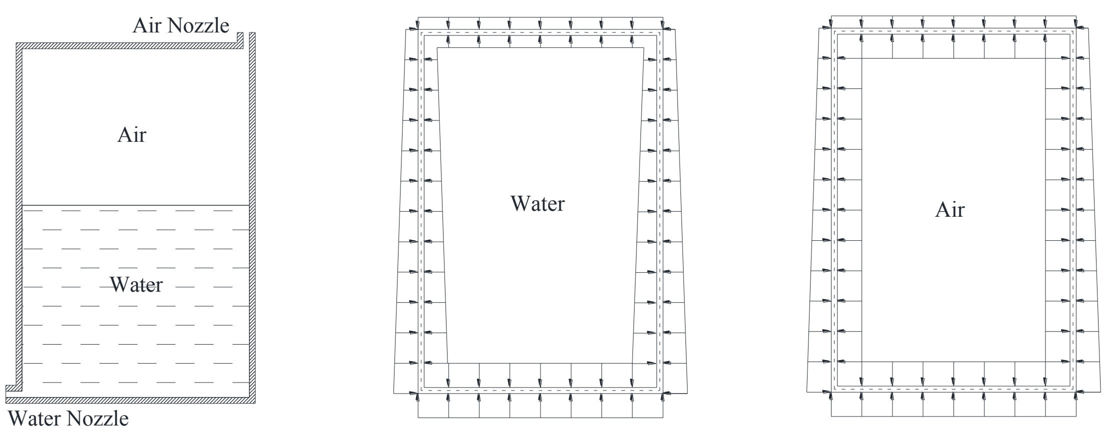
TABLE 1. TYPICAL VALUES OF CONCRETE PROPERTIES

3. LOAD CHARACTERIZATION

A schematic configuration of the storage vessel is shown in Figure 4(a). The air nozzle is on the top of the vessel, and the water nozzle is at the bottom. In the energy storage process, the compressed air is injected from the air nozzle and the water is expelled out. In the energy retrieval process, the air nozzle is open with the outlet air pressure being lower than the hydrostatic pressure at the air-water interface. Then the surrounding seawater will flow in and expel the compressed air out.

The external hydrostatic pressure is nearly constant, and the internal pressure changes during the charge/discharge process. The air-full state and water-full state are shown schematically in Figure 4(b) and Figure 4(c). These two cases are studied as the upper and lower bounds to envelop intermediate states. Figure 4(b) shows the external and internal pressure distribution when the storage vessel is full of water, in this case there is no differential pressure generated. Figure 4(c) shows the external and internal pressure distribution when the storage vessel is full of air. It can be observed that the internal pressure (air pressure) is uniform and equal to the hydrostatic pressure at the air-water interface (at bottom). The maximum external and internal differential pressure occurs at the roof of the storage vessel. With the increasing depth (from top to the bottom) the differential pressure on the side wall decreases and eventually become zero. It should be noted that both Figure 4(b) and Figure 4(c) show the idealized cases. Also the total internal pressure is higher than the total external pressure so the loading applied on the storage vessel is imbalanced. The uplift force needs to be balanced by the anchoring force outside.

For the rectangular tank configuration, the anchoring force is from the ballast on the top. For the cylinder the anchoring force is from the suction caisson at the bottom. Typically, seawater has a standard absolute temperature of 283 K, a salinity of 35 ppm, and a density of ρ_w = 1025 kg/m^3. For air at 288.2 K and 101.33 kPa, the density of air is ρ_{air} = 1.225 kg/m^3. Even though the compressed air density will be higher than the standard value, it is still much smaller than seawater density, and therefore the compressed density is not considered in the analysis. Assuming deployment in a water depth is 300 m, the differential pressure (external pressure – internal pressure) on the roof in one operational loading cycle (24 hours) is plotted in Figure 5. The magnitude of differential pressure on the roof is proportional to the height of the storage space.



(A)SCHEMATIC CONFIGURATION **(B)WATER-FULL STATE** **(C)AIR-FULL STATE**

FIGURE 4. THE SCHEMATIC CONFIGURATION OF STORAGE VESSEL AND TWO EXTREME STATES DURING ONE OPERATIONAL CYCLE

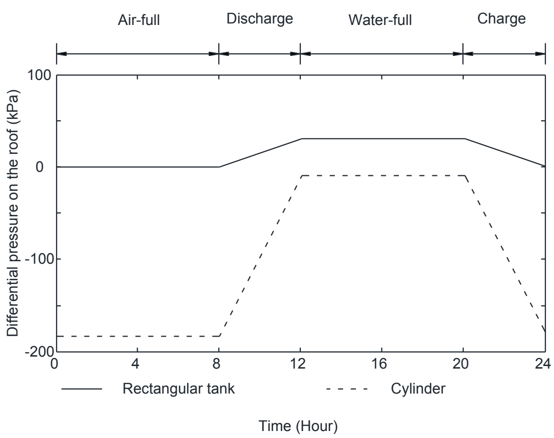


FIGURE 5. DIFFERENTIAL PRESSURE DURING ONE OPERATIONAL CYCLE

4. MODELING RESULTS

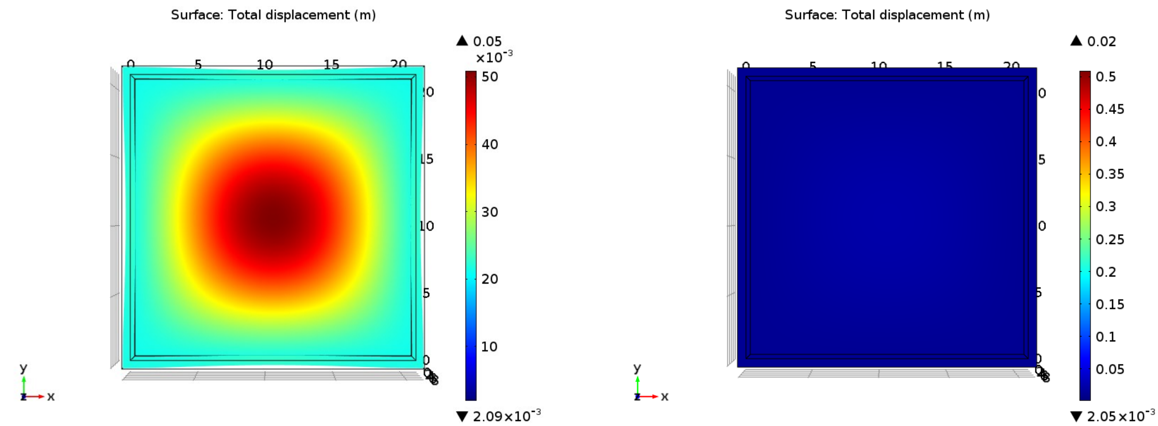
The concrete vessel is modeled as perfect elastic material. The seabed soil is simplified as spring foundation with equivalent stiffness (Winkler soil model). The modulus of subgrade reaction (spring stiffness) is assumed to be 45,360 kN/m^3 (Rao 2010).

The rectangular configuration and cylindrical configuration are modeled in 3D using COMSOL. The material properties are listed in Table 1 and the results are summarized in Table 2. The displacement and tensile/compressive stress distributions of the rectangular tank and the cylinder at air-full and water-full states are plotted in Figure 6, Figure 7, Figure 8 and Figure 9, respectively. For the rectangular configuration, the maximum displacement occurs at the edge of roof when the vessel is full of water, because the ballast on the top of the vessel acts as additional load on the roof. However, when the vessel is full of air, the load induced by the ballast is taken as anchoring force and balanced by the differential pressure on the roof (difference between internal air pressure and external water pressure).

Compared to the rectangular configuration, in which the anchoring force (the ballast buoyant weight) is applied on the top of the vessel, the anchoring force of the cylindrical vessel is from a suction caisson driving its capacity from interaction with the soil at the bottom. Correspondingly, the maximum displacement and maximum tensile stress of the cylindrical vessel occurs at the center of roof at the air-full stage and the maximum tensile stress is 4.5 MPa, which is within the range of tensile strength of reinforced concrete (19.1 MPa).

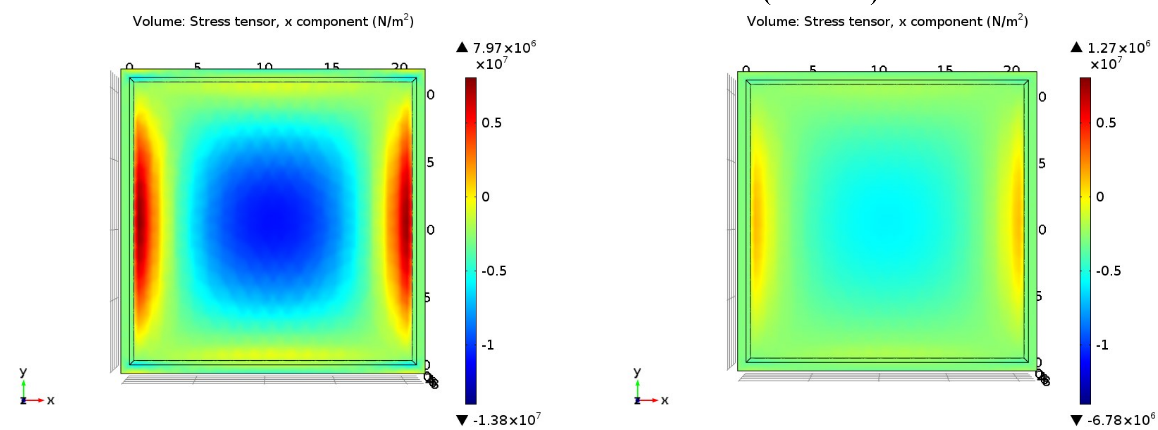
		Max displacement (mm)	Max tensile stress (MPa)	Tensile Strength (MPa)
Rectangular configuration	Air full	20	1.3	19.1
	Water full	50	8	
Cylindrical configuration	Air full	25	4.5	
	Water full	32	-	

TABLE 2. MAXIMUM DISPLACEMENT AND MAXIMUM TENSILE STRESS OF RECTANGULAR TANK



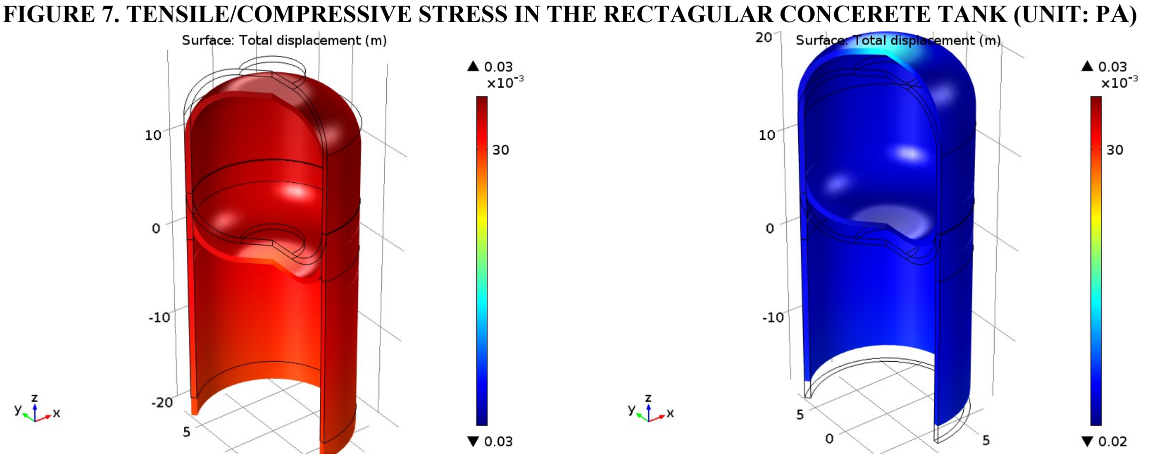
WATER-FULL STATE AIR-FULL STATE

FIGURE 6. DISPLACEMENT OF RECTANGULAR CONFIGURATION (UNIT: M)



WATER-FULL STATE AIR-FULL STATE

FIGURE 7. TENSILE/COMPRESSIVE STRESS IN THE RECTAGULAR CONCERETE TANK (UNIT: PA)



WATER-FULL STATE AIR-FULL STATE

FIGURE 8. DISPLACEMENT OF CYLINDRICAL CONFIGURATION (UNIT: M)

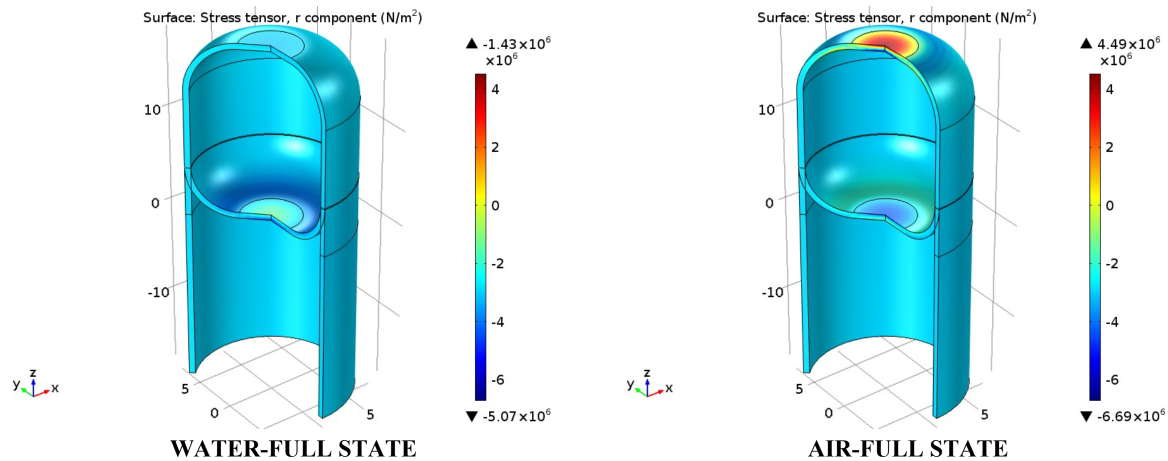


FIGURE 9. TENSILE/COMPRESSIVE STRESS IN THE CYLINDRICAL CONFIGURATON (UNIT: PA)

5. SUMMARY AND CONCLUSIONS

In this paper, a rectangular concrete tank and a cylindrical concrete vessel are considered as configurations for OCAES vessels, and their behavior under operational loading is studied. On the basis of the results obtained, the following conclusions can be drawn:

1. The magnitude of operational load (differential pressure) on the roof is proportional to the height of storage space.
2. For the rectangular configuration with ballast on the top, the maximum tensile stress occurs at the edge of roof at water-full state. For the cylindrical configuration with suction caisson at the bottom, the maximum tensile stress occurs at the center of roof at air-full stage.
3. Both ballast and suction caisson are considered as anchoring solutions. Ballast provides the anchoring force on the top of the vessel, which mainly induces the additional compressive stress in the sidewall. Suction caisson provides the anchoring force on the bottom of the vessel, which mainly induces the additional tensile stress in the sidewall.

ACKNOWLEDGMENTS

This work has been funded by the Ocean Energy Engineering Program of the UNC Coastal Study Institute. The authors would also like to thank Professor Billy Edge, Head of Coastal Processes and Engineering at the UNC Coastal Studies Institute for his support and leadership of this program.

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APPENDIX A: FACTOR OF SAFETY FOR CONCRETE TANK

The thickness of ballast on the top of concrete tank is designed to be 5m. Consequently the safety factor (include both the ballast weight and storage vessel weight) will be

$$FS = \frac{\rho_c V_v + \rho_b (1-n) V_b}{\rho_w V_v + \rho_w (1-n) V_b + \rho_w V_s} = 1.32 > 1.3 \quad \text{(A1)}$$

Where

ρ_w = the density of seawater, ρ_w =1025 kg/m^3;

ρ_c = the density of concrete, ρ_c =2300 kg/m^3;

ρ_b = the specific density of ballast, ρ_b =2100 kg/m^3;

n = the porosity of ballast, n =0.5;

V_t = total volume of concrete tank calculated on outer dimension,

$V_t = 21.2m \times 21.2m \times 9.2m = 4135m^3$;

V_s = storage volume of concrete tank calculated on inner dimension,

$V_s = 20m \times 20m \times 3m = 1200m^3$;

V_b = volume of ballast on the top of the storage tank, $V_b = 20m \times 20m \times 5m = 2000m^3$;

V_v = the volume of material for the storage vessel,

$V_v = V_t - V_s - V_b = 935m^3$.

APPENDIX B: STORAGE VOLUME OF CYLINDRICAL CONFIGUATON

Half of the cross-section (r-z plane) of storage space can be subdivided into four zones and integrate over φ, as shown in Figure B1. The volume of each component can be calculated respectively

$$V_A = 17m \times 3m \times 2\pi \times 1.5m = 480.6m^3 \quad \text{(B1)}$$

$$V_B = 4.5m \times 8m \times 2\pi \times (3m + \frac{4.5m}{2}) = 1188m^3 \quad \text{(B2)}$$

$$V_{C1+C2} = \frac{\pi(4.5m)^2}{2} \times 2\pi \times (3m + \frac{4 \times 4.5m}{3\pi}) = 981m^3 \quad \text{(B3)}$$

So the total volume of cylindrical storage space is

$$V = V_A + V_B + V_{C1+C2} = 2650m^3 \quad \text{(B4)}$$

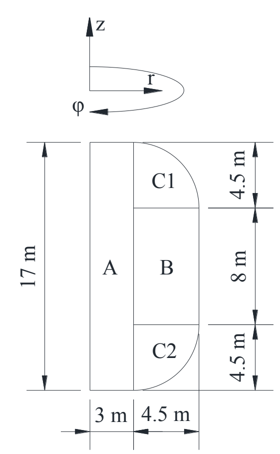

FIGURE B1. HALF OF CROSS-SECTION OF STORAGE SPACE

APPENDIX C: STORAGE CAPACITY

Assume the air compression is an ideal isothermal process (100% efficiency), the storage volume can be calculated as:

$$W = PV \ln \frac{P}{P_a} \quad \text{(C1)}$$

Where

W is the energy storage capacity

V is the storage volume

P_a is the atmosphere pressure, equal to 1 atm.

P is the desired compression pressure, which is about 30 atm. corresponding to the water depth of 300 m.

For the rectangular configuration, the volume is 1200 m^3, the corresponding energy storage capacity is 12,400 MJ. For the cylindrical configuration, the volume is 2650 m^3, the corresponding energy storage capacity is 27,400 MJ.