Marine Structures 60 (2018) 122–135

Contents lists available at ScienceDirect

Marine Structures

journal homepage: www.elsevier.com/locate/marstruc

Seismic response of a submarine tunnel under the action of a sea wave

Xuansheng Cheng[a,*], Guoliang Li[a], Jia Chen[a], Kai Zhang[a], Xiuli Du[b]

[a] School of Civil Engineering, Lanzhou University of Technology, Lanzhou, 730050, PR China
[b] Key Laboratory of Urban Security and Disaster Engineering of Education, Beijing University of Technology, Beijing, 100124, PR China

ARTICLE INFO

Keywords:
Sea wave
Subsea tunnel
Earthquake
Fluid-solid interaction
Dynamic response

ABSTRACT

In this paper, taking the Jiaozhou Bay Subsea Tunnel with a curved wall in Qingdao as the research background, while assuming that the liquid cannot be compressed and considering the effect of surface gravity waves, a harmonic wave is used to simulate a sea wave. Considering coupling effect of stress and seepage fields, dynamic responses of subsea tunnels under the action of ocean waves and earthquakes are discussed. The results show that with an increase in water depth, the maximum equivalent stress, the first principal stress, the third principal stress and the displacement of the tunnel structure all increase. When the water depth reaches a certain value, the influence of sea waves on the calculation results is so small that it can be ignored, and the influence of the sea wave on the displacement is smaller than that on the stress. After considering sea waves, the increases of velocity and acceleration with different sea water depths are far less than 5% under the action of an earthquake. The influence of sea waves on dynamic responses of subsea tunnels may not be considered when the sea water depth is more than 40 m.

1. Introduction

Subsea tunnels have many advantages such as providing convenience for people to travel, greatly alleviating the problem of carrying capacity, promoting regional economic development, solving traffic problems across straits and gulfs and avoiding the most unfavorable factors (sea waves, water erosion, weather changes including freezing and thawing, etc.) without interfering with ship navigation. Such tunnels are widely constructed in coastal areas and have great research value. Chen et al. [1] used Finite Element Method (FEM) to simulate the influence of tidal load on the stability of lining and rock mass surrounding a tunnel under the coupling of stress and seepage based on the tidal phenomena in the Xiamen's subsea tunnel. Fang et al. [2] regarded the rock mass as an isotropic continuum medium, studied two aspects of the problem of groundwater seepage caused by the subsea tunnel excavation, and defined the essence of water pressure in a porous medium. Li et al. [3] analyzed a subsea tunnel where natural drainage cannot be adopted and seawater level change is relatively smaller than tunnel buried depth, and where both ends of the tunnel exit are higher than the bottom of the sea. Liu et al. [4] analyzed the seismic response of a super large diameter subsea tunnel under high earthquake intensity by using dynamic FEM and determined the weak parts of the vault and arch waist under the action of an earthquake and dead weight. Li et al. [5] analyzed the stability of a subsea tunnel under the interaction of rock mass surrounding tunnel and water body and performed fluid-solid interaction (FSI) model testing. According to the feature of FSI model testing, a new FSI model test system that can be used for simulation of quasi-three-dimensional plane stress and plane strain was developed. Liu et al. [6] studied the deformation of a subsea tunnel based on cooperative theory and chaotic dynamics theory and determined that

* Corresponding author.
E-mail address: chengxuansheng@gmail.com (X. Cheng).

https://doi.org/10.1016/j.marstruc.2018.03.004
Received 14 November 2016; Received in revised form 24 November 2017; Accepted 17 March 2018

the entire process can be divided into equilibrium evolution, non-equilibrium linear evolution and non-equilibrium nonlinear evolution. Li et al. [7] studied the seismic response of a tunnel structure on the ground of underwater saturated soil mass by applying the pore pressure element of FSI two-phase medium dynamic model to simulate saturated soil. Manolis and Parvanova [8] studied the seismic response of non-uniform and multi-layer geological underground tunnels by using the finite difference and boundary element method. Wang et al. [9] noted that choosing reasonable strength criteria of rock/soil in rock/soil mechanics engineering is the basis of a reasonable analysis and carried out elastic-plastic analysis of a subsea tunnel considering the seepage. Our group has carried out extensive research in tunnel seepage, FSI, shock absorption, construction method and stability [10–15].

A sea wave is the phenomenon of water fluctuation that is caused by the external force of the sea water. The subsea structural environment is complex because of the complexity and particularity of wave loads. Scholars have carried out some research on the influence of sea wave on the structure. Venkataramana and Kawano [16] used energy spectrum to simulate ocean waves and studied the nonlinear dynamic response of ocean structures under the action of ocean waves and earthquakes using FEM. Cai et al. [17] studied the bucket foundation breakwater, which is suitable for deep water and soft soil embankment at the bottom of the seabed. Zhao et al. [18] studied the dynamic response of a pile-soil-water system under wave load by means of the characteristic function of scattering of a wave on a pile. Taking the Tanhai artificial island structure for an example, Cai et al. [19] selected different strength reduction factors to consider different weakening degrees of wave load on the seabed on the basis of the previous research results according to the three characteristic water levels (design high water level, design low water level and climax water level of once-in-a-century) and combining with the actual situation of the study area. Nian et al. [20] noted that the water pressure caused by waves is a factor that needs to be considered in the structural design and obtained that the wave has a negative effect on the stability of the seabed slope.

In summary, at present, most of the research focused on the seismic response, coupling of seepage and stress fields, different geological environments and other aspects on subsea tunnels, and the study of the dynamic response of ocean waves on subsea tunnels has not yet been reported. In this paper, taking the Qingdao Jiaozhou Bay Subsea Tunnel with a curved wall as the engineering subject, assuming that the liquid is incompressible, considering the liquid surface gravity wave effect, and assuming that the sea wave surface is the free surface, a harmonic wave is used to simulate a sea wave. Under the coupling of the stress field and seepage field, the dynamic response of the subsea tunnel under the action of an ocean wave and earthquake is discussed, and a theoretical basis is provided for the seismic design of subsea tunnel structures.

2. Coupling calculation of seepage and stress fields

2.1. Action mechanism

The influence of stress fields on the seepage field is mainly reflected by the change of porosity. Assuming that unit volume is V, change in volume is ΔV, porosity is n, and volume change of rock mass is ΔV_s, there is the following relationship between each quantity, namely

$$\mathrm{d}\Delta V_s = (1-n)\mathrm{d}\Delta V + \Delta V \mathrm{d}(1-n) \tag{1}$$

that is

$$\begin{aligned} \mathrm{d}n &= (1-n)\frac{\mathrm{d}\Delta V}{\Delta V} - (1-n)\frac{\mathrm{d}\Delta V_s}{\Delta V_s} \\ &= (1-n)\mathrm{d}\varepsilon_V + (1-n)\mathrm{d}\varepsilon_s \approx -(1-n)\mathrm{d}\varepsilon_V \end{aligned} \tag{2}$$

In Eq. (2), $\mathrm{d}\varepsilon_V$ is the volumetric strain of unit volume and $\mathrm{d}\varepsilon_S$ is solid volumetric strain.

So

$$\begin{cases} \frac{\partial n}{\partial t} = -(1-n)\frac{\partial \varepsilon_V}{\partial t} \\ \frac{\partial \Delta V}{\partial t} = -\Delta V \frac{\partial \varepsilon_V}{\partial t} \end{cases} \tag{3}$$

Given that

$$dP = -E_w \frac{d\Delta V_w}{\Delta V_w} \tag{4}$$

where E_w is water elastic modulus, P is water osmotic pressure, and ΔV_w is volume change of water.

By the mass conservation law, $\rho\Delta V_w$ is a constant, and the total differential form is

$$d(\rho\Delta V_w) = 0 \tag{5}$$

where ρ is water density.

That gives

$$\Delta V_w d\rho + \rho d\Delta V_w = 0 \tag{6}$$

Hence,