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RESEARCH ON CRACK DEPTH MEASUREMENT IN CONCRETE BY USING RAYLEIGH WAVES

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ABSTRACT

The possibility of crack depth measurement in concrete by using Rayleigh waves and the feasibility of measurement method are3 introduced in this paper. The principle of crack measurement in concrete by using in-plan Rayleigh waves and the measurement analysis method are studied by using finite element method.

KEYWORDS

Rayleigh Wave; Dispersion Characteristics; Dispersion Curve; Concrete; Crack Measurement;

INTRODUCTION

It is a common phenomenon cracks occur in concrete during the hydraulic or waterpower construction. Due to sharp fluctuation of temperature, cubic deformation of concrete, evaporation of water, unequal settlement and , various construction conditions, cracks of different depth form in dams. They do a great harm to structures. Therefore it is necessary to detect cracks and acquire their states and relevant parameters. Only through in can we judge the degree of the damages done by cracks and discuss to take corresponding strengthening measures. States of cracks in the outside structure and parameters mainly refer to the width and depth of cracks. Crack width is the width of the crack surface, which is generally measured with calibrated magnifiers or crack calipers. Crack depth ,the depth from the crack surface in the concrete to the closed end of crack ,is the most essential parameter indicating the state of cracks. In fact, crack measurement in concrete is Crack Depth Measurement.

Ultrasonic wave diffraction method is the main method to measure crack depth. Research on it is relatively extensive and a lot of improvement on it has been done(Sick 1979). However,ultrasonic wave diffraction method still has following problems: (a). It cannot detect deep cracks for ultrasonic wave diffraction method cannot receive real first wave signals when it is used to detect deep cracks. Up until now, the maximum measurement depth is about 0.8 m . (b). It is difficult to judge states of cracks when cracks are filled with water. Ultrasonic perpendicular waves can penetrate through cracks full of water and combine themselves with diffraction wave signals, which add difficulty to acheive accurate judgement. (c). Ultrasonic perpendicular wave method only has effect on the concrete with few reinforced bars or none. In case of concrete with bars penetrating through cracks, the distance between two probes should be 1.5 times longer than *d*(*d* is crack depth). If re-bars are vertical to cracks and densely arranged, this method is invalid. In addition of ultrasonic wave diffraction method drilling-hole measurement method and penetrating radar measurement method(Cantor 1984) are both in use . But the former is costly because it requires to drill holes, and the latter has short measurement depth for electromagnetic waves will be absorbed by water.

From the above, a great number of pioneering researches on deep-layered crack measurement in concrete have been done since the 1950s at home and In-situ. Many measurement methods are developed, but we have not solved the problem of deep-layered crack measurement in concrete effectively.

While external loading (hammers etc.) is acting on the earth surface, waves in foundation propagate mainly in form of Rayleigh waves(Miller 1995), whose energy accounts for 67.3% of total wave energy. Energy of P waves (perpendicular waves) does 6.9% and energy of S waves(shear waves) does 25.8%. What's more , R-waves attenuate slowly horizontally whereas they do quickly vertically. The valid propagation depth of Rayleigh waves is about 1.5 times as long as their wave lengths. Surface waves have been widely used for acquiring earth parameters of foundation in Civil Engineering(Chen 1993,Wu 1997), so they can be used to detect crack depth in concrete. Propagation characteristics of R-waves are to be introduced next.

1.FUNDAMENTAL CHARACTERISTICS OF RAYLEIGH WAVES

A kind of surface waves exists around the boundary of elastic half space . Rayleigh studied them firstly, so this kind of surface waves were was generally named Rayleigh waves. We can get the velocity V_R of R-waves in homogeneous elastic half-space. It can be given as(Wu 1997):

$$v^3 - 8v^2 + 8\frac{2-\mu}{1-\mu}v - \frac{8}{1-\mu} = 0 \qquad (1)$$

in which $v = V_R^2/V_S^2$, V_S is the velocity of shear waves in half-space, μ is Poisson's ratio. According to equation (1), the root of this cubic formula is only determined by Poisson's ratio of the material concerned while it is irrelevant to the oscillation frequency. In other words , V_R is a constant value which has no frequency dispersion. If μ is given, we can determine the corresponding value of V_R, which is the velocity of R-waves. In addition, equation (1) can be approximately expressed as:

$$V_R = \frac{0.862 + 1.14\mu}{1.0 + \mu}V_S \qquad (2)$$

Horizontal displacement U and vertical displacement V of R-waves in half-space can be written(Wu 1997) as(without consideration of time factor):

$$U = Aik\left[\exp(-aky) - \frac{(1+b^2)}{2}\exp(-bky)\right]\cdot\exp(ikx) \qquad (3)$$

$$V = Ak\left[\exp(-aky)\cdot a - \frac{(1+b^2)}{2b}\exp(-bky)\right]\cdot\exp(ikx) \qquad (4)$$

where A is an arbitrary constant, $i = \sqrt{-1}$, $k = \omega/V_R$ is wave number, $a = \sqrt{1 - V_R^2/V_P^2}$, $b = \sqrt{1 - V_R^2/V_S^2}$, V_P is the compression wave velocity. Equation (3) indicates that displacement of particles of surface waves attenuates rapidly along depth(in Y direction). Its fluctuation component is quite small at the site where the depth is one wave long. Its amplitude is only 20% of that on surface. We can figure out the penetrating length of the surface wave through altering its oscillation frequency. When we study different features of some material, that means altering the sampling depth. The above mentioned characteristics are not available through pe P wave measurement or S wave measurement.

If the oscillation of surface wave is a sine one, phase difference of adjacent points P_a and P_b is ϕ, and distance between the two points is L ,it yields that:

$$V_R = \frac{2\pi f L}{\phi} \qquad (5)$$

where f(= $\omega/2\pi$) is oscillation frequency. From this equation, we can see that ϕ is linearly related to f with V_R fixed.

2. SURFACE-BREAKING CRACKS' INFLUENCE ON PROPAGATION OF SURFACE WAVES

According to elastic fluctuation theory, Achenbach(1981) has analyzed the mechanism of surface waves' propagation through surface-breaking cracks. When surface waves propagate through surface-breaking cracks in homogeneous elastic media (Fig.1), wave conversion occurs at the openings and apexes of cracks, triggering incidence, reflection and diffraction. It leads to no disastrous consequence to ignore the minute body waves produced by diffraction. We can apply the analytical method analyze components, which are generated when surface waves pass through cracks, of the reflection, vertical incidence and diffraction. Then by superimposing them we can obtain forward propagating surface waves through cracks as well as rearward propagating surface waves due to the reflecting effects of the cracks. Combining them with the incident waves. we will acquire the two-phase surface waves. However. this numerical procedure seems extremely complex and time-consuming. There exists difficulty in applying it to analyze damped media, while concrete is a kind of damped media. This paper applies finite element method to analyze the characteristics of surface wave propagation through cracks. This method has many applications, such as damped media and elastic-plastic media, and high accuracy. Easy operation is another feature of this method.

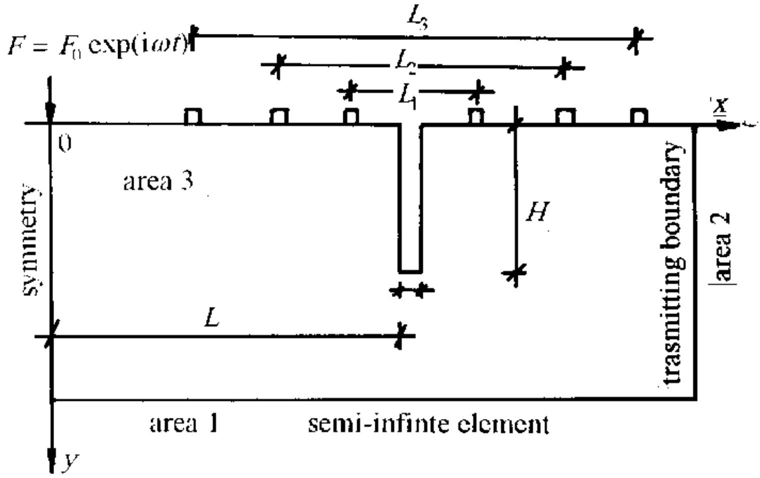


Fig. 1 Concrete Crack Measurement

3. NUMERICAL METHOD

Finite element method is the most widely used method in civil engineering analysis. This method is convenient for calculating and has strong applicability. Finite element method is also widely used in dynamic response analysis. In foundation dynamic response analysis, the most crucial problem is the boundary procession due to radiation of wave energy to foundation. Improper procession will lead to the occurrence of reflection waves and ultimately the distortion of results. Xia(1996) introduces a boundary processing method to analyze stable dynamic response. This method simulates the body waves, which possesses a small part of total energy, with ele semi-infinite element in the vertical direction (area 1 in Fig.1) and it simulates surface waves with transfer boundary (area 2 in Fig.1). Area 3 is subdivided in finite element.

4. NUMERICAL EXAMPLES

Here is a problem limited in a symmetry plane. All the relevant parameters of concrete are dimensionless. Velocity of shear wave $V_S = 1.0$, mass density $\rho = 1.0$, crack depth H=2.0, crack width d =0.15, Poisson's Ratio μ =0.35, damping coefficient ξ =0.01. External loading is point loading. Its amplitude F_0=50. Probes of detectors are clamped to the banks of the crack symmetry. We analyze the differences of phase angles wherever the 3 pairs of probes are located respectively. Figures 2,3,4 show the relationship of phase difference ϕ and oscillation frequency ω separately when $L_1 = 2.15, L_2 = 4.15, L_3 = 6.15$. Vibration center is 6.0 away from the crack when frequency exceeds 1.5. Otherwise the distance is 10.0.

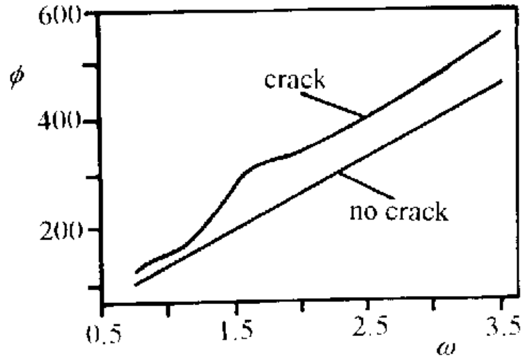


Fig. 2 Relationship of ϕ and ω ($L_1 = 2.15$)

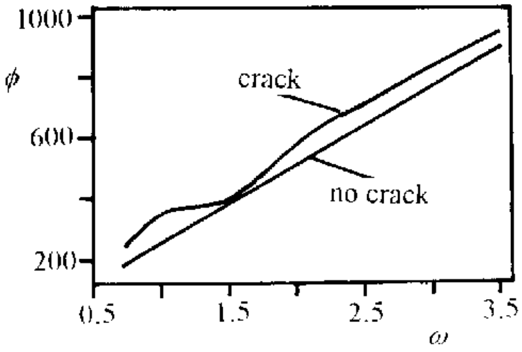


Fig. 3 Relationship of ϕ and ω ($L_2 = 4.15$)

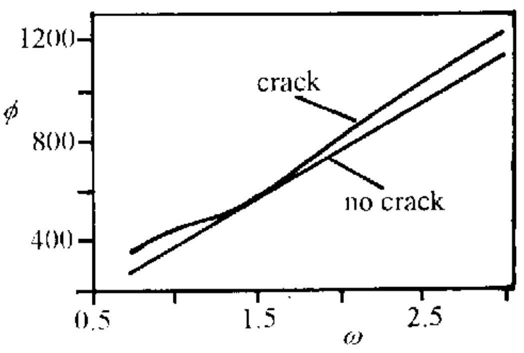


Fig. 4 Relationship of ϕ and ω ($L_3 = 6.15$)

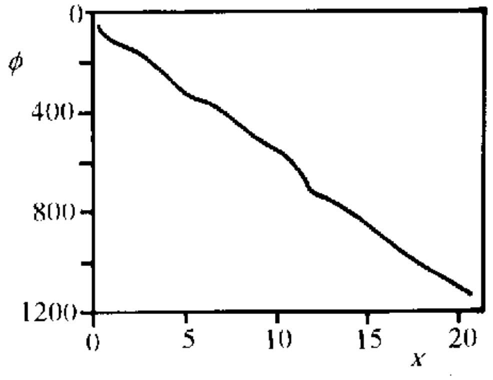


Fig. 5 Relationship of ϕ and x ($\omega = 0.75$)

According to the figures, we can infer that ϕ is in linear relation to ω in an uncracked medium. Phase difference ϕ increases in an cracked medium. In addition, ϕ is no longer linearly related to ω. Generally, the higher is wave frequency, the larger is the ϕ. The crack's hindrance done to surface wave is so-called vibration isolation.(Fig.8) Equation (4) indicates that phase difference ϕ is in linear relation to the distance L. However, that is not the case that in cracked area reflection waves, triggered by cracks, are superimposed with incidence waves. It has some fluctuations. (Figures 5,6,7). If wave frequency is low (wave length λ is longer than depth H), ϕ is not linearly related to ω. The probable causes can be low damping, short distance between Waves can propagate through cracks with considerable phase deviation around the cracks.

Vibration center and the crack or decrease of wave width limited to a symmetry plane problem. ϕ has a sharp variation when ω =1.5(λ = 3.85). Based on this phenomenon, we can conclude ω = 1.5 is the characteristic frequency. Therefore, we obtain the valid depth coefficient $\eta = H/\lambda \approx 0.5$. Fig. 8 shows the relationship between the distance x and vertical displacement of surface particles under the conditions that ω =0.75 and ω=3.5. From the figures, we observe that cracks isolate oscillation of high-frequency surface waves while they seldom hinder the propagation of low-frequency surface waves.

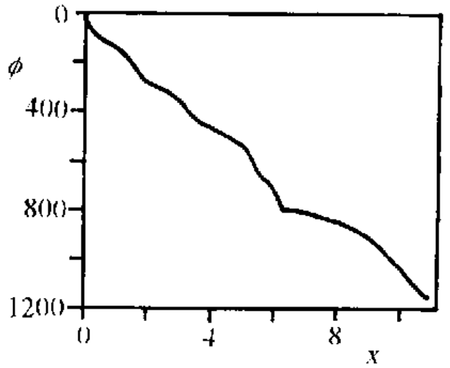


Fig. 6 Relationship of ϕ and $x(\omega = 1.5)$

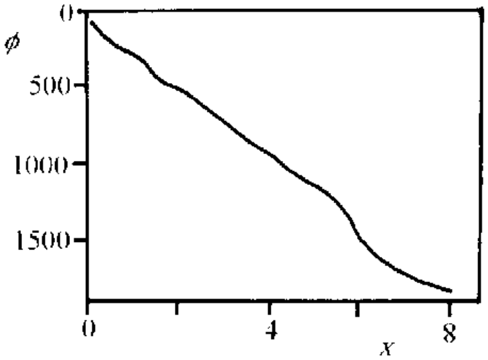


Fig. 7 Relationship of ϕ and $x(\omega = 3.5)$

5. CONCLUSIONS

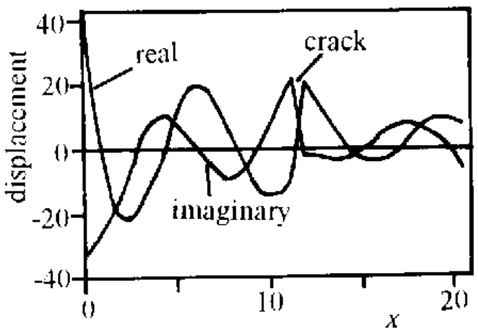
This paper discusses the mechanism of crack measurement in concrete by using surface waves. We also do some simulations with finite element method to get the conclusion as following:

1)Phase differene ϕ in cracked media is quite larger than that in uncracked media when incident wave has a high frequency. Linear relationship does not exist between ϕ and ω. Neither does between ϕ and x. Their relationship curve has some fluctuations. Cracks considerably impede surface waves. That is so called oscillation isolation.

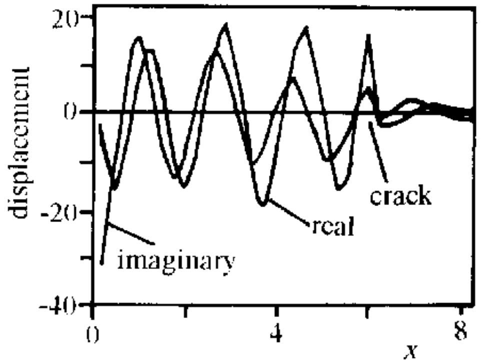
2)Phase difference ω is not in linear relation to ω under the circumstance of low oscillation frequency($\lambda > H$). ϕ is larger than that in uncracked media. Cracks exert less influence on surface waves, but some on phase angles.

3)Fluctuations of ϕ is large when incident waves have high frequency, the characteristic frequency. The vali

depth coefficient is about 0.5. urther research on other types of problems expects more accurate coincidence with experimental fac



(a) $\omega = 0.75$



(b) $\omega = 3.5$

Fig. 8 Vertical displacement of surface particle

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