Effects of Maximum Shear Modulus on Soil Dynamic Properties and Seismic Response of Soil Layer

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ABSTRACT : Maximum shear modulus is one of the most important parameters effecting shear modulus ratio, damping ratio and seismic response of soil. Usually, maximum shear modulus is determined by strain method in laboratory, rather than by shear velocity method in-situ, and based on it, shear modulus ratio and damping ratio of soil can be provided. The effect of maximum shear modulus by shear velocity method and shear strain method on shear modulus ratio, damping ratio and seismic response of soil are studied. And, the relationship of shear modulus ratio and damping ratio for two methods is established. The results shows that the effects of maximum shear modulus on shear modulus ratio, damping ratio and seismic response of soil are obvious and should not be neglected.

1. INTRODUCTION

In the actual engineering, one-dimensional equivalent linear method of soil earthquake response on the basis of the wave motion model is used to analyze seismic response of soil layer. Dynamic properties of soil, including maximum shear modulus, curve of dynamic shear modulus ratio and damping ratio relation curve of damping ratio with shear strain must be taken into account(Chen, 2007), and maximum shear modulus(MSM) is the key parameter determining both dynamic shear modulus ratio and damping ratio. However, difference of maximum shear modulus acquired by various methods is obvious, which leads to great disparity of dynamic shear modulus ratios and damping ratios made by different methods to the same soil sample. MSM can be gained through in_lab and in_situ tests. Usually, non-linear parameters are obtained through in_lab test(strain method), and MSM is gained by in_situ test(shear velocity method), whose mismatch is yielded. That is, MSM is obtained using different method during acquiring curve shear modulus ratio, damping ratio and computation. In engineering practice, the computation method of acquiring shear modulus ratio and damping ratio is well recognized. Whether the above way of dealing with MSM is reasonable or not needs to be further studied. It is scare to find such reports about the influence of maximum shear modulus on dynamic shear modulus ratio, damping ratio, and on seismic response of soil presently. Aimed at the problems mentioned, the paper introduces the acquiring method of MSM, and based on it, the effects of MSM obtained by shear velocity method and strain method on Soil dynamic properties and seismic response of soil layer are studied as a case of site of big bridge along Tao'er River in Binzhou, China. At the same time, the relationship of shear modulus and damping ratio for two methods is established. The results obtained have certain reference values for soil parameter tests and seismic response analysis of soil layer.

2. DETERMINING METHOD OF CURVE OF DYNAMIC SHEAR MODULUS RATIO, DAMPING RATIO OF SOIL WITH SHEAR STRAIN AND MSM

Dynamic shear modulus ratio and damping ratio of soil can be measured through triaxial test or resonance pillar testing at present(Yuan, 2000) and the latter method is adopted this time. Dynamic shear modulus G and damping ratio λ with different shear strain are measured directly through self-vibration pillar apparatus. Equivalent linear modulus is used to describe relation of dynamic shear modulus and damping ratio with shear strain. Shear modulus adopt the results of free vibration after torsion. The $\lambda_{\max}$ and n_λ can be obtained by fitting curve of $\lambda - (1 - G/G_{\max})$ plotted by double-logarithm coordinate. The description is as follow (Zhuang, 2005):

$$G/G_{\max} = \frac{1}{1 + \gamma/\gamma_r} \tag{2.1}$$

Where, $G_{\max}$ is MSM; G is the shear modulus with shear strain; γ is shear strain amplitude and γ_γ is the reference shear strain.
Damping ratio of soil, λ, changes with strain amplitude, and can be described by the following empirical equation:

$$\lambda = \lambda_{\max} \left(1 - G/G_{\max}\right)^{n_\lambda} \tag{2.2}$$

Where, $\lambda_{\max}$ is maximum of damping ratio and n_λ is fitted index(Shi, 1989).
MSM is usually measured by the following two methods:
(1) Test strain method: It is ordinarily assumed that all kinds of skeleton curves of soil can be approximated to the hyperbola Eqs.[3] without exception, leading to Eqs.[4].
Shear stress is expressed as

$$\tau = \frac{\gamma}{a + b\gamma} \tag{2.3}$$

Where, a and b are testing parematers correlated with soil property.
Shear modulus is expressed as

$$G = \frac{1}{a + b\gamma} \tag{2.4}$$

When γ equals to 0, a equals $1/G_{\max}$ leading to $G_{\max} = 1/a$; $b = 1/\tau_{\max}$ and $\tau_{\max}$ is maximum shear stress when shear strain tends to be infinite.
(2) Shear velocity method: According to wave propagation theory, equation between maximum shear modulus $G_{\max}$ and shear velocity is expressed: $G_{\max} = \rho v_s^2$.Where, ρ is density of soil sample and v_s is shear velocity measured in_situ.

3. INFLUENCE OF MAXIMUM SHEAR MODULUS ON SOIL DYNAMIC SHEAR MODULUS RATIO AND DAMPING RATIO

As a case of one site(Table 1) of big bridge along Tao'er River in Binzhou, 8 soil samples are gained from boreholes, and tested to obtain dynamic parameters of soil using free vibration method by the multi-function resonance pillar machine in Institute of Engineering Mechanics(IEM), China(Liu,2007). In particular, it was noted that velocities of site soil up to 70 m are measured in_situ because of collapse of soil borehole, and the other velcocities beyond 70 m are obtained by empirical expressions(Bo, 1998). It can be seen in the Table 1 that this engineering ground primarily consists of silty clay, silty soil and silty sand, and that there are the phenomenon of interlayer of silty soil and silty sand, silty clay and silty soil. $G_{\max}$ is gained by strain method and shear velocity method, denoted by $G_{\max,\gamma}$ and $G_{\max,v_S}$ respectively, and listed in Table 2.

Table 1 Site condition

No.	Thickness of layer/m	Depth of layer bottom/m	Description of soil	Density/ g • cm^{-3}	Shear velocity/ m • s^{-1}	Sample number and its overlying depth
1	0.90	0.90	Earth fill: yellow; very dense; wet- saturated	1.95	140.0	
2	1.30	2.20	Silty clay:brown;soft-plastic; saturated	1.98	135.0	
3	3.00	5.20	Silty soil: brown; very dense; saturated	1.96	166.8	
4	5.20	10.40	Silty sand: brown; very dense; saturated	1.98	163.8	
5	3.30	13.70	Silty clay:brown;soft-plastic; saturated	1.96	166.6	S1: 13.4-13.6
6	0.45	14.15	Silty sand: brown-yellow; very dense; saturated	1.95	172.0	
7	4.25	18.40	Silty soil: brown-gray; very dense; saturated	1.96	180.8	S2: 15.4-15.6
8	2.10	20.50	Silty sand: brown-yellow; very dense; saturated	1.96	184.0	S3: 19.0-19.2
9	3.10	23.60	Silty soil: brown-gray; very dense; saturated	1.97	187.6	S4: 22.2-22.4
10	2.20	25.80	Silty clay:brown;soft-plastic; saturated	1.98	186.0	S5: 25.3-25.5
11	0.60	26.40	Silty soil: brown-gray; very dense; saturated	1.99	188.0	
12	1.00	27.40	Silty clay:brown-gray;plastic; saturated	1.98	190.0	
13	0.90	28.30	Silty soil: brown-gray; very dense; saturated	1.96	191.7	
14	11.30	39.60	Silty clay:brown-gray; plastic; saturated	1.97	212.3	S6: 34.6-34.8
15	1.60	41.20	Silty soil: brown-gray; very dense; saturated	1.95	226.8	
16	5.60	46.80	Silty sand: brown; dense; saturated	1.99	229.0	
17	7.60	54.40	Silty clay:brown-gray; plastic; saturated	1.96	253.5	S7: 49.6-49.8
18	7.00	61.40	Silty soil: brown-gray; very dense; saturated	1.97	322.0	S8: 59.6-59.8
19	2.10	63.50	Silty clay:brown-gray; hard-plastic; saturated	2.00	328.0	
20	1.70	65.20	Silty soil: brown-gray; very dense; saturated	1.95	330.0	
21	4.80	70.00	Silty clay:brown-gray; hard-plastic; saturated	1.97	335.0	
22	1.40	71.40	Silty soil: brown-gray; very dense; saturated	1.98	338.1	
23	3.60	75.00	Fine sand： brown;dense; saturated	1.96	428.3	

24	4.50	79.50	Medium sand：brown;dense; saturated	1.97	407.9
25	6.50	86.00	Fine sand：brown;dense; saturated	1.98	441.5
26	3.70	89.70	Silty clay:brown-gray; hard-plastic; saturated	1.96	499.8
27	1.3	91.0	Silty clay:brown-gray; hard-plastic; saturated	2.00	503.1

Table 2: MSM determined by shear strain method and shear velocity method

	Soil Sample No.							
	S1	S2	S3	S4	S5	S6	S7	S8
$G_{\max,\gamma}$ /Mpa	28.3	83.0	99.5	85.9	117.8	135.8	50.6	147.9
$G_{\max,v_s}$ /MPa	54.4	64.0	66.4	69.3	68.5	88.8	125.9	201.1

Usually, data of shear strain, shear modulus and damping ratio tested from resonance pillar test in a range of small strain are quite reliable(Yuan, 2005). But MSM can't be measured by test directly and is obtained by fitting method. According to wave propagation theory, velocities from in_situ test can reflect really comprehensive states of soil, and thus it is reasonable that MSM is obtained using shear velocity method in calculation. It is supposed that shear strain, shear modulus and damping ratio measured by in_lab test can truly reflect the real state of soil, because of difficulty of their test. Based on the same data of shear strain, shear modulus and damping ratio tested in the lab , MSM determined by shear strain method and shear velocity method is introduced to study the effects of MSM on dynamic shear modulus ratio and damping ratio, as shown in Fig.1. In Fig.1, the lateral axis is shear strain; the left vertical axis is dynamic shear modulus ratio $G/G_{\max}$, and the right vertical axis is damping ratio λ. In Fig.1, solid line is the result of shear strain method, and dashed line the result of shear velocity method.

Comparison and analysis from the results of Fig.1 and Tab.2 show that MSM determined by shear strain method and shear velocity method and its effects on shear modulus ratio and damping ratio maximum shear modulus is obvious. The result of Table 2 shows that the difference of MSM determined by the two methods are so great, even more than 100%, and that no laws can be found. Combined with Tab.2, it can be found from the results of Fig.1: (1) when maximum shear modulus determined by shear velocity method is larger than that of shear strain method, dynamic shear modulus ratios obtained by the two method have proportional relation, the result determined by shear velocity method is smaller than that of shear strain method, and the damping ratio determined by the former method is larger than that of the latter method in the mass; (2) when the maximum shear modulus determined by the former method is smaller than that of the latter method, the dynamic shear modulus ratio of the former method has already been larger than 1 and it's not able to get the damping ratio because it's an abnormal result in a case.

In addition, relationship of shear modulus ratio and damping ratio determined by the above two methods is deduced according to Eqs(2.1) and Eqs(2.2):

$$\frac{G_d/G_{\max,v_S}}{G_d/G_{\max,\gamma}}=\frac{G_{\max,\gamma}}{G_{\max,v_S}},\lambda_{V_S}=\lambda_{\max,V_S}\left(1-\frac{G_d}{G_{\max,V_S}}\right)=\lambda_{\max}\left(1-\frac{G_d}{G_{\max,\gamma}}\times\frac{G_{\max,\gamma}}{G_{\max,v_S}}\right) \quad (3.1)$$

Where, $G_{\max,\gamma}$ is the fitted parameter; $G_{\max,v_S}$ is calculated by wave propagation theory. According to Eqs(3.1), dynamic shear modulus ratio determined by shear velocity method is smaller than that of shear train method when $G_{\max,v_S}$ is greater than $G_{\max,\gamma}$, and there is unreasonable phenomenon that damping ratio is

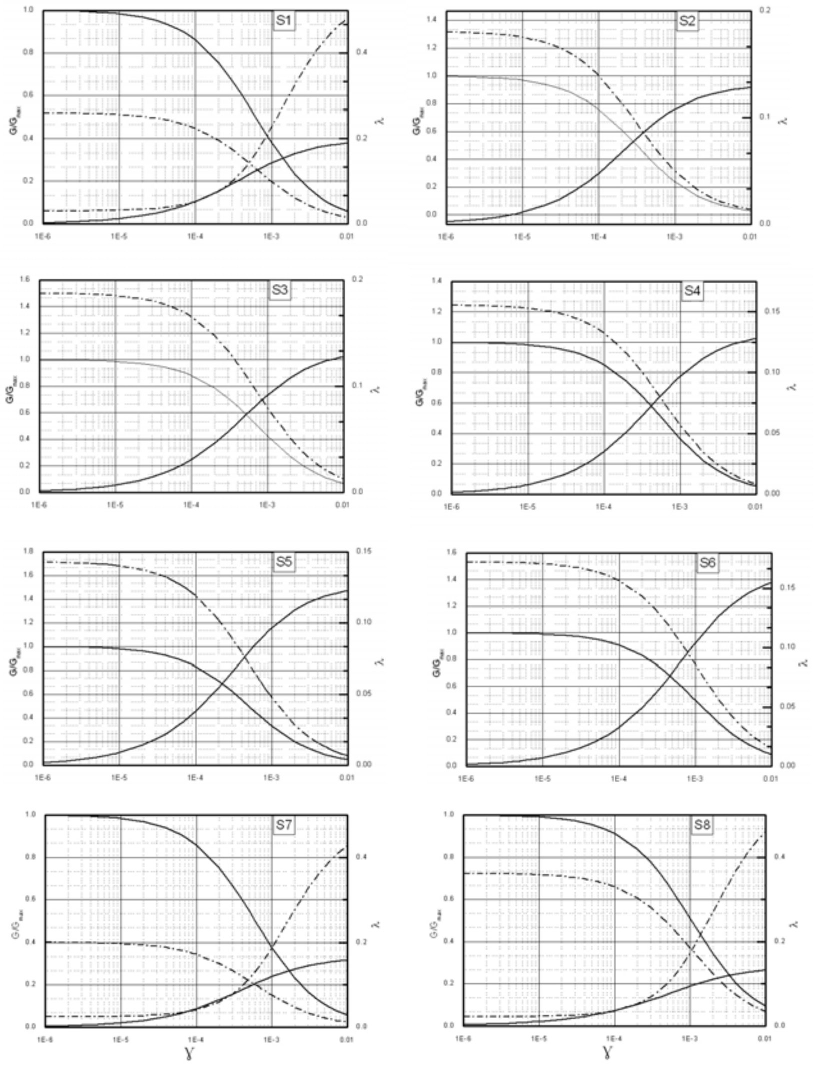


Fig. 1 Influence of MSM on dynamic shear modulus ratio and damping ratio

negative because of $1-\frac{G_d}{G_{\max,\gamma}}\times\frac{G_{\max,\gamma}}{G_{\max,v_s}}<0$ when $G_{\max,V_S}<G_{\max,\gamma}$ and $G_d\rightarrow G_{\max,\gamma}$. The above analysis is correct in practice.

4. INFLUENCE OF MAXIMUM SHEAR MODULUS ON SEISMIC RESPONSE OF SOIL LAYER

4.1. Calculation of seismic response of site

The analysis of seismic response of site selected are implemented. SN acceleration record of peak 318.82 Gal of El Centro wave in 1940 is adopted as earthquake input, as shown in Fig.2. Peak ground acceleration is scaled to 50 Gal and 100 Gal in calculation, denoted by P1 and P2 respectively. The shear modulus ratio and damping ratio adopted in calculation are gained by shear strain method, and MSM are obtained by the two method in Tab.2 respectively. The results are shown in Fig.3 and Fig.4. Line A is the result of shear strain method, whereas line B is the result of shear velocity method.

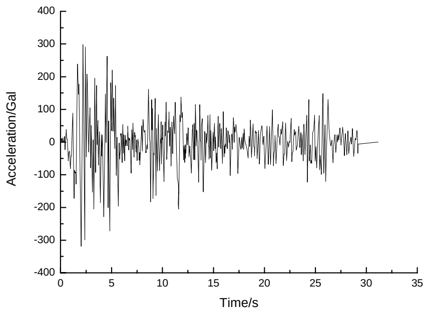
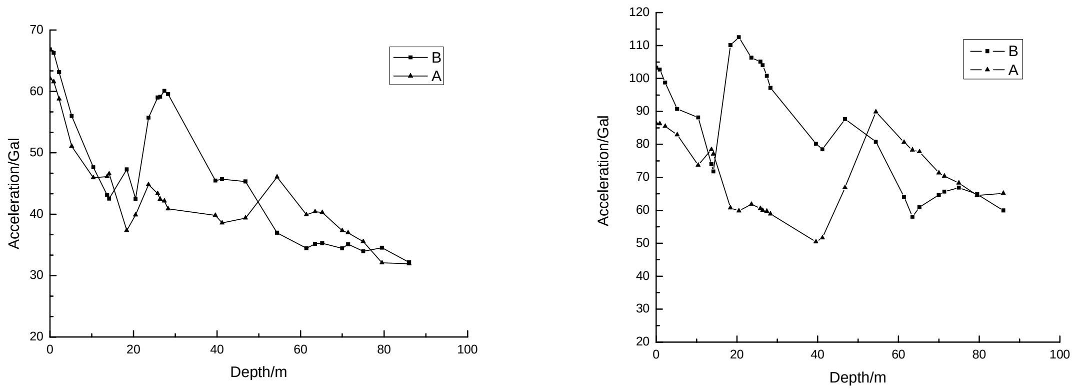


Fig. 2 Time history of acceleration

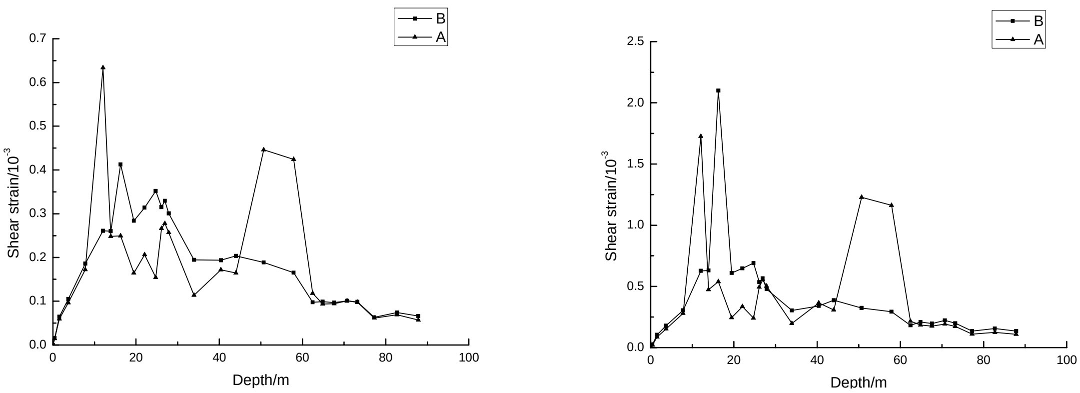
4.2 Analysis of calculating results

This article only presents parts of calculation results, because of the limited space. The influences of maximum shear modulus on peak acceleration and shear strain of soil Fig.3 and Fig.4 are shown in Fig.3 and Fig.4. According to the calculation results and the figures, the effects of maximum shear modulus on seismic response of soil have characteristics as follows:



(a) earthquake input P1 (b)earthquake input P2

Fig. 3 Effects of maximum shear modulus on peak acceleration



(a) earthquake input P1 (b)earthquake input P2

Fig. 4 Effects of maximum shear modulus on shear strain of soil

(1)The influence of MSM on surface peak acceleration and distribution of acceleration with depth is notable, especially as inputs of more intense strength. Fig.3 shows that the discrepancy of surface peak acceleration of the two methods reach 7% when the peak acceleration of earthquake input equals to 50 Gal; while it attains to 20% when the peak acceleration of earthuqake input equals to 100 Gal. The peaks of acceleration with soil are obviously different. The change of distribution of peak acceleration is greater with stronger input. In addition, the result of shear velocity method is larger than that of shear strain method in shallow part.
(2)It can be shown from the curve of shear strain with depth that: shear strain changes greatly at points where MSM by two method is different , whereas there are no changes or minor influence in the other parts.

4. CONCLUSION

There are many affecting factors on maximum shear modulus, including composition of soil, sedimentary environment and history, confirmation of test means, etc. This paper primarily discusses the influence of maximum shear modulus on dynamic shear modulus ratio, damping ratio and seismic response of soil. The result obtained of this paper indicates that the influence of maximum shear modulus on dynamic shear modulus ratio, damping ratio and seismic response of soil is remarkable and the discrepancy of surface peak acceleration attains to 20% when the peak acceleration of earthuquake input equals to 100 Gal. How to measure maximum shear modulus exactly is a problem that is worthy to study further. It's suggested that in_situ tests should be developed as well as advanced new testing methods and compared to the results in lab.

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