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The study of borehole test error of theshear-wave velocity at typical engineering sites in China

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Abstract

Shear-wave velocity(Vs) plays an important role in geotechnical engineering and earthquake engineering. This research was aimed to figure out the test bias of the in-situ test and to show off the law of it. Based on this theme, we selected three different sites in Harbin(China) and invited several test teams to finish 30 times repeated borehole tests of each site. Statistics method had been used to define the test error. The most significant founding of the test is that the in-situ test error kept at the similar level of the whole test depth which is from 0 to 40m from the ground surface. We figured out that the test error obey the Normal distribution. The Standard Deviation(SD) of the test might be around 15%. Moreover, the ground water level and soil properties do not have obvious influence on the test bias. By finishing this research, we can estimate the change of correlation parameters to the Vs.

Keywords: round-robin test; shear-wave velocity test; test error; statistical parameter; normal distribution;

1. Introduction

Shear-wave velocity(Vs) is a basic and important parameter of the soil. It can be used to calculate related geotechnical parameters, describe the soil stiffness, determine the potential of the liquefaction and so on. Because of its natural and basic characteristics, the reliable of the in-situ Vs test become more and more important. The Vs profile can be obtained by several kinds of methods. The representative methods are down-hole test, P-S suspension logging test, cross-hole test, seismic cone(SCPT), seismic dilatometer(SDMT) and surface wave method. In this paper, we focused on the most wildly used method down-hole and P-S suspension logging test. By analyzing the test error of these two method, we can find the "true" accuracy and reliable of the borehole Vs test.

In China, the main research area of the in-situ Vstest is to get the statistical Vs-Depth and then engineers may estimate the Vs of unreachable sites. At 1984, Zhou and Wang[1] had showed off the general rules between Vs and the depth by counting 500 group down-hole test results. The relationship can be fitted by a exponential or logarithmic formula. In the following thirty years, some other researchers promoted the development of this statistical work through a huge number of the in-situ test results. Some of the most representative research are as followed: Gao and Liu[2] finished the research on the Hefei expansive soil and proved the depth-velocity relationship obey the index formula. Liu and Zheng[3] pointed out that except the silt soil, Vs of other kinds of soil can be estimate by several formulas. Qiu and Bo[4] figured out that the fitting feasibility was decided by the kind of the soil. It is very hard to got Miscellaneous Fill velocity relationship. For most kinds of the soil, the polynomial and exponential fitting are both reasonable. Zhang[5] collected shear-wave velocities from 365 borehole drills and then figured out the relationship between Vs and the depth. The results showed that there was a obvious fitting between the velocity and the depth. In summary, all these researchers had finished lots of meaningful work on the Vs in-situ test, but there is still a blank of the description of the test error.

International researchers have also noticed the Vs test error. Some specific research had been done and some meaningful conclusions had been published. In 1988, some US researchers[6] had finished the test in Turkey Flat. They finished approximate 20 times of the Vs round-robin test. The results were given by the down-hole, P-S suspension logging, cross-hole and surface wave method. This test proved the objective existence of the velocity test error. With the development of site survey, more and more researchers moved the eye to the test error. Kim[7] invited some units with various shear-wave velocity testing methods and then finished a round-robin test in one site. The result proposed some ways to improve the accuracy of the test results. Xia et al[8] tried to made a formula to estimate the bias of the shear-wave velocity through the surface wave test results. The parameters of the formula included logger number of channels, sample rate, source location and some other inspects. The results showed that the Vs30 bias given by this method was around 1%. Asten and Boore [9] gave out a lot of results about the shear-wave velocity test. They fetched the velocity by using down-hole method, P-S logging, SCPT, MASW, SASW method. They figured that the deviation of Vs30 was nearly 4.8%. Thompson et al[10] studied the test results of down-hole test, SCPT and surface wave method. They pointed out that the test uncertainty could be neglected when the soil layer was less than 10m with special test environment. Marosi and Hiltunen[11] studied the results given by surface-wave method and pointed out that the shear-wave velocity test results had the deviation about 5% to 10%. This bias may enhanced with the increase of the depth and the changing of the soil properties. Thelen et al[12] used ReMi and down-hole test to get the shear-wave velocity of LA basin. In order to estimate the deviation, they invited three institutes to calculate the same original data. They got the conclusion that the deviation of Vs30 was between 2% to 14%. Boore et al[13] reviewed the surface wave test method. They pointed out that several reasons would enlarge the test bias. Mahmoud et al[14] compared different kinds of test method and pointed out each kind of the methods had its own outcome and shortage. All the methods may have the inspects which will cause the test error. F.Garofalo et al[15][16] gave out the research conclusions about the velocity test bias of the surface wave test method. They invited several research teams to analyze the original surface wave test results. They reported that the bias can be reduced with the improvement of the surface wave method.

All these research results show that the shear-wave velocity test error is an objective reality. But now we still lack of a method to describ its accuracy and the reliability. For the purpose of getting Vs results more resonable, we selected three typical engineering sites at Harbin in China and then finished a specific experiment on the borehole shear-wave velocity test error and analyzed its distribution. Finally, we got the accuracy and reliability on typical engineering sites.

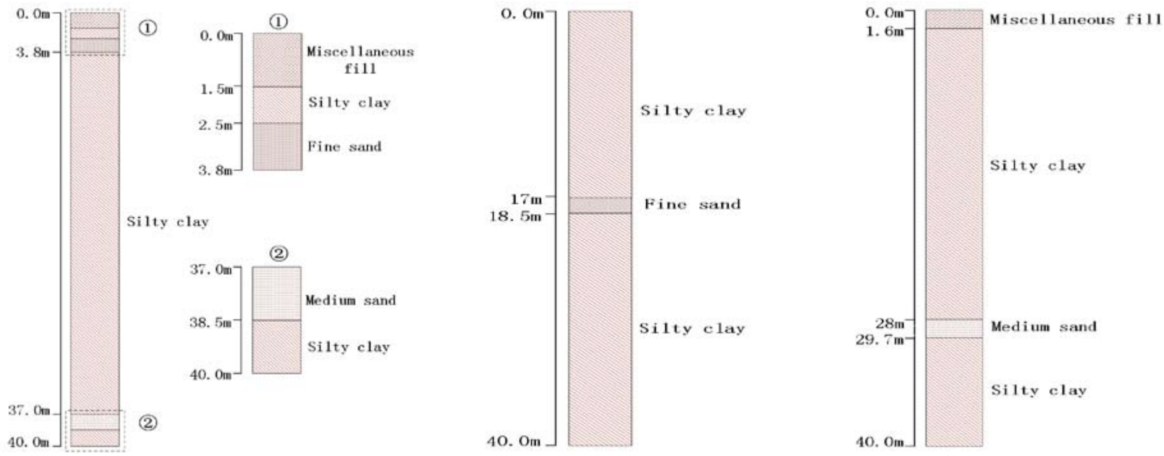
2. The in-situ round-robin test

In order to study the shear-wave velocity test error, eight facilities(include the author's research group) had finished the in-situ round-robin test. They were composed by two universities, three research institute and three companies. All the members are reliable and rich in test experience. They repeated the borehole Vs test on each site for 30 times and then we got 90 groups of Vs for all three sites. For the authenticity of the round-robin experiment, each team was asked to show their original wave form results. Seven groups finished the test by using down-hole method and another one gave out the results by P-S logging test. Eighty times of down-hole test and ten times of P-S logging test have been done.

It is highly noticed that this study focused on the test error, so that we do not discuss the instruments used in the test. We mixed all the data together for the analysis. All the tests were finished in two days after drilling. Site characteristics are shown in Table 1. Histograms of drillings on each site is reported in Fig.1.The common characteristics of the three experiment sites was that their bedrocks are both thicker than 40m. The soil properties are the silty clay with the thin sand layer. There was a miscellaneous fill layer at both Site 1 and Site 3.

Table 1-Sites environmentle characteristics

Site No	Site characteristics	Environmental Noise	Groundwater Level
1	Green belt near the construction site	Next to the road , noisy.	5m
2	In the forest, little grass, flat ground	200m to the nearest road, little noise	33m
3	Little grass, flat ground	100m to the nearest road, little noise	26m



a)Drill of Site 1 b)Drill of Site 2 c)Drill of Site 3

Fig .1- Histograms of drillings

After summer up all the results of the round-robin test, we built the Vs test database to analyze the test error.We decided to use several parameters to describe the test error based on statistical theory. The definitions are as followed.

$Vs_{(Data)}$- each of the Vs test result.

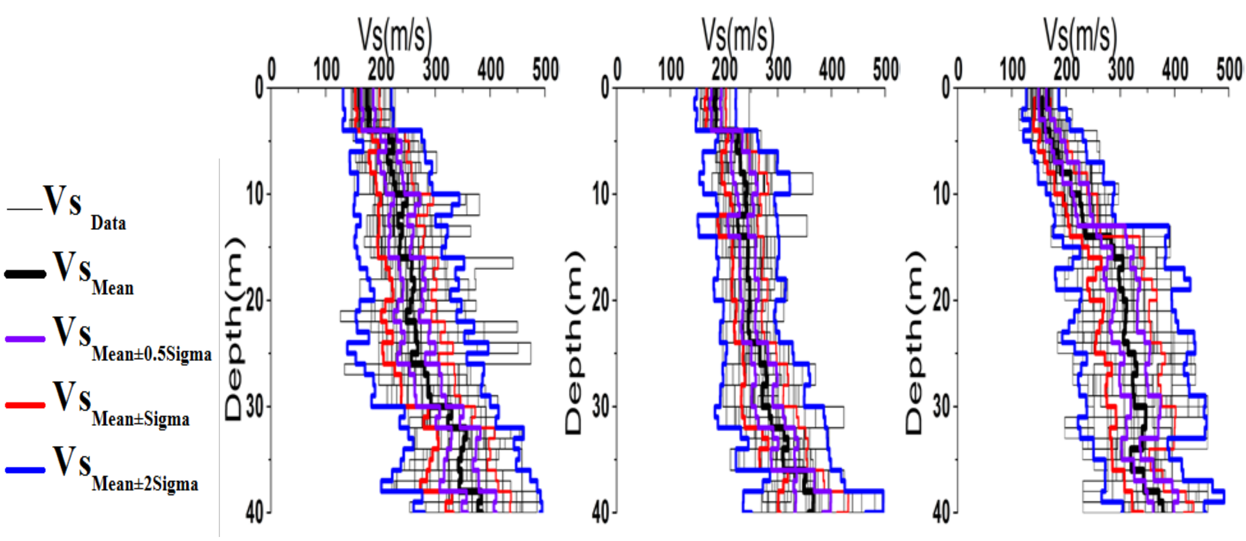
$Vs_{(Mean)}$ -the arithmetic average of 30 times Vs round-robin test. It is calculated meter by meter.

$Vs_{(Mean \pm 0.5Sigma)}$- $Vs_{(Mean)}$ plus or minus 0.5 times standard deviation(SD) of Vs test. Shows the range of 1 deviation of $Vs_{(Mean)}$.

$Vs_{(Mean \pm Sigma)}$- $Vs_{(Mean)}$ plus or minus 1 times SD of Vs test. Shows the range of 2 deviations of $Vs_{(Mean)}$.

$Vs_{(Mean \pm 2Sigma)}$- $Vs_{(Mean)}$ plus or minus 2 times sSD of Vs test. Shows the range of 4 deviations of $Vs_{(Mean)}$.

In statistics, $Vs_{(Mean)}$ represents the "true" value of the in-situ test. Also, metric standard deviation shows the data variability range.$Vs_{(Mean \pm 0.5Sigma)}$, $Vs_{(Mean \pm Sigma)}$ and $Vs_{(Mean \pm 2Sigma)}$ had characterize the different degrees of velocity test error. These parameters described the test error of each site preliminarily. The test results are shown in Fig.2.



a)Site 1 b)Site 2 c)Site 3

Fig.2- Round-robin test results for three sites

We added up the in-situ test results of each site and got the preliminary statistical result as followed. The results are calculated through mixing all the test data together meter by meter. Each site has 1200 Vs data (the test depth is 40meters, and each meter have 30 groups of Vs test results) for the total. We define as a statistics sample and counted the data distribution range. It is shown in Table 2.

Table 2- Preliminary statistics results of the test results

Vs distribution range	Site 1	Site 2	Site 3
$Vs_{(Mean-0.5Sigma)}$ to $Vs_{(Mean+0.5Sigma)}$	30%	36%	37%
$Vs_{(Mean-Sigma)}$ to $Vs_{(Mean+Sigma)}$	58%	66%	69%
$Vs_{(Mean-2Sigma)}$ to $Vs_{(Mean+2Sigma)}$	82%	90%	92%

The distribution range are similar of these three sites. We reported that the data concentration of Site2&3 is a little higher than that of Site 1. It is highly noticed that this is the overall statistics result. According to the definition in statistics[17], when the bias is in the range of 1 to 2 SD, it means the data is doubtable. When the bias is larger than 2SD, the data is unreliable. Based on these principle, the doubtable data is 34%,34%,33% of site 1,2,3. The unreliable data of Site 1,2,3 is 18%, 10% and 8%. According to Fig.1,the soil properties of these three sites are nearly the same. Only one obvious difference is the environmental noise. We considered it is the main reason that influence the wave form and then the layer to layer analysis process. It made more unreliable data.

3.All sites test deviation analysis

In part 2, we build the database and analyzed it preliminarily. These three sites are similar in soil properties and the distance of each other is less than 6km. Because of that, we pushed forward the further analysis of the totally test bias by summer up all the data together. First, we analysis each site test bias by turning the real Vs results into the bias percentage. This step take all the bias in to percentage account and turn the bias in to a non-dimensional parameter. Second, we mixed all these bias percentage together and then figured out the statistics law of these three typical engineering sites. The authors found out the model of the distribution. Finally, we reported the changing rules of the test bias of the typical engineering in Harbin.

In order to figured out the test bias of the three sites, we defined the $Vs_{(mean)}$ as the reference axis and then calculated the relative bias percentage to describe the test error.

The test error measured by percentage was calculated as formula (1)

$$Bias_{(Data)}=(Vs_{(Data)} - Vs_{(Mean)}) / Vs_{(mean)} \times 100\% \quad (1)$$

Then we got other parameters to describe the test error as followed:

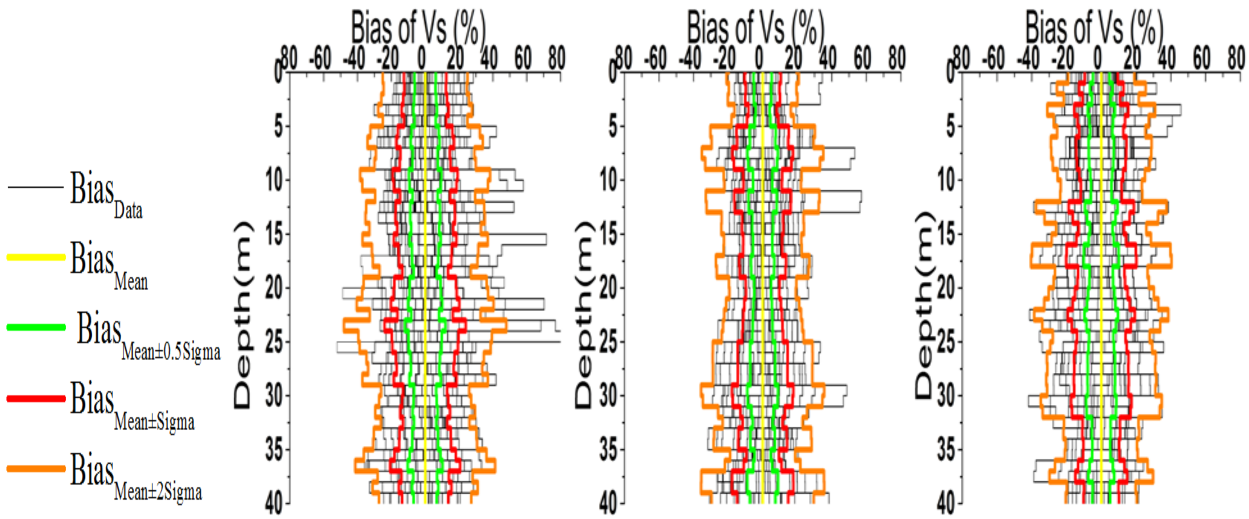
$Bias_{(Mean)}$ -the mean of the Vs test error. The value is approximate 0.

$Bias_{(Mean \pm 0.5Sigma)}$-$Bias_{(Mean)}$ plus or minus 0.5 times standard deviation of the bias. Shows 1SD range of the bias.

$Bias_{(Mean \pm Sigma)}$-$Bias_{(Mean)}$ plus or minus 1 times standard deviation of the bias. Shows 2SD range of the bias.

$Bias_{(Mean \pm 2Sigma)}$-$Bias_{(Mean)}$ plus or minus 2 times standard deviation of the bias. Shows 4SD range of the bias.

By using formula 1, we got the test bias of each site. The results is shown in Fig.3. The bias distribution had been shown in Table 2.



a)Site 1 b)Site 2 c)site3

Fig.3-Test error of each site(measured by percentage)

These sites are the typical engineering working sites in Harbin. The test bias is similar in three site. Each site's results are not enough to build the distribution law of the Vs test bias. Therefore the three sites are likely have the similar bias. When we put all the data together ,we can define the test bias as a statistics parameter. We got the results shown in Fig.4. By doing this, we transformed the real shear-wave velocity test error into dimensionless test error which was measured by percentage.

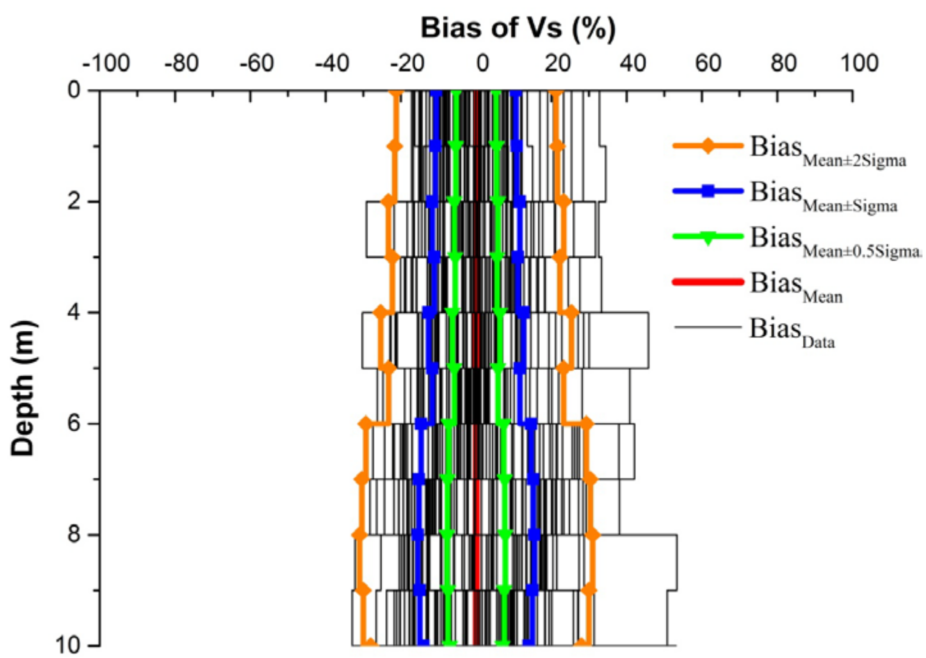
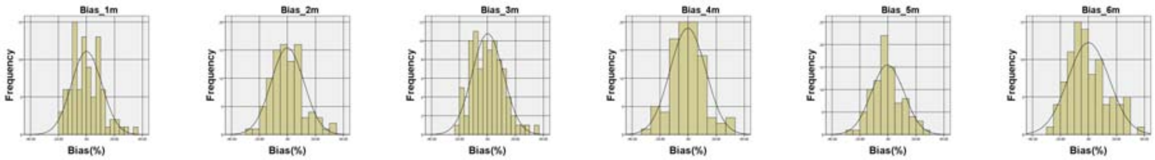
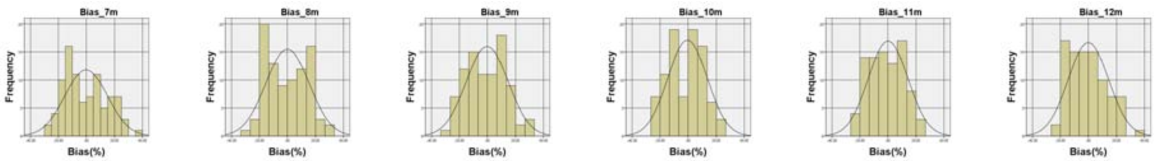


Fig.4-Summary of the three sites test error

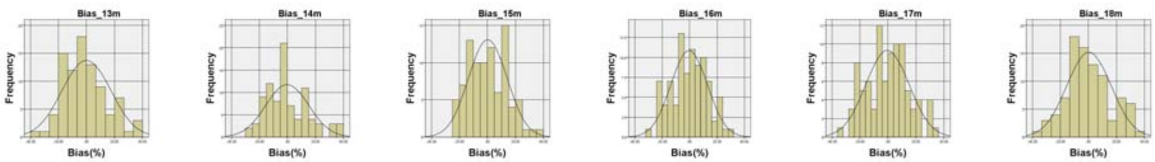
The test bias now have obvious distribution form. Then we fitted the test error by SPSS software for seeking the distribution of the test error. Although the degree of kurtosis and discrete in fitting is slightly different, the results indicated that the test error is nearly the mound distribution of every meter. The per-meter fitting results are shown in Fig.5.



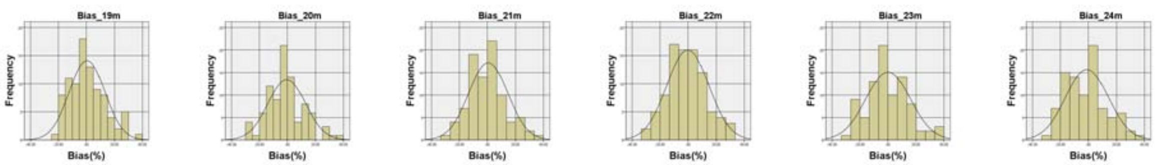
a)Fitting results from 1 to 6 meter



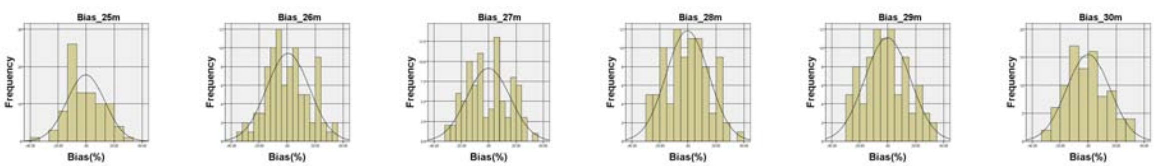
b)Fitting results from 7 to 12 meter



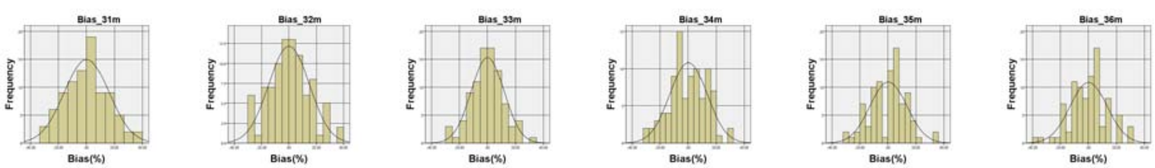
c)Fitting results from 13 to 18 meter



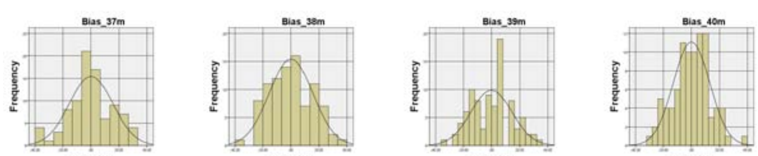
d)Fitting results from 19 to 24 meter



e)Fitting results from 25 to 30 meter



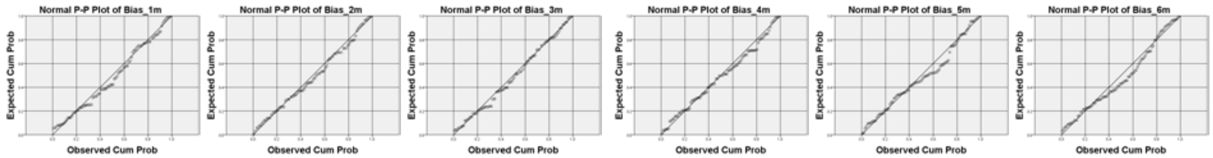
f)Fitting results from 31 to 36 meter



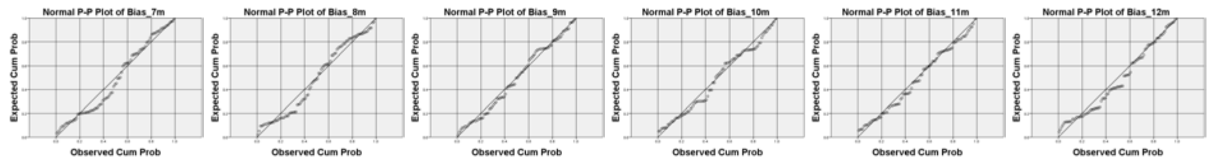
g)Fitting results from 37 to 40 meter

Fig.5-Statistics fitting of the test error

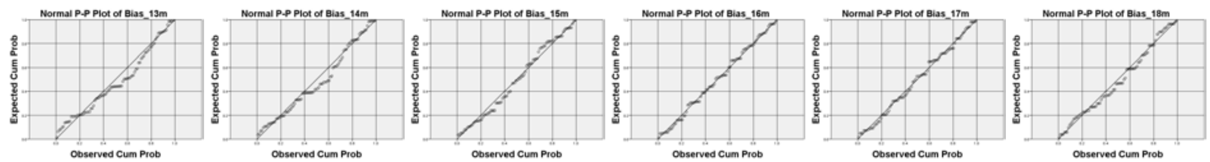
By evaluating the per-meter statistical results, we figured out that the SD was between 10% and 18%. The bias didn't show significant change from the bottom to the surface. Now the distribution looks like obey the normal distribution. Then we used P-P diagram to exam it. If the results is just stay in line, it means the results obey the normal distribution. The meter by meter results are shown in Fig.6.



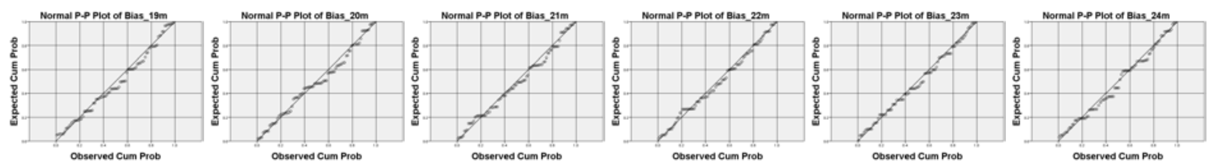
a)P-P distribution diagram results from 1 to 6 meter



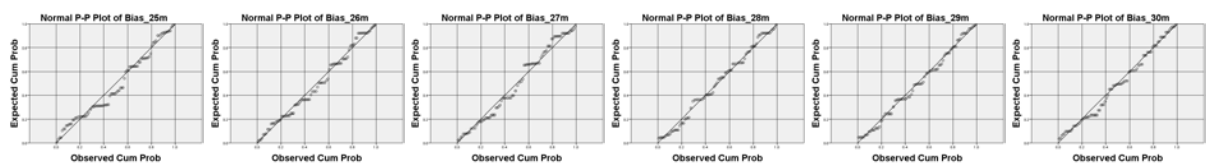
b)P-P distribution diagram results from 7 to 12 meter



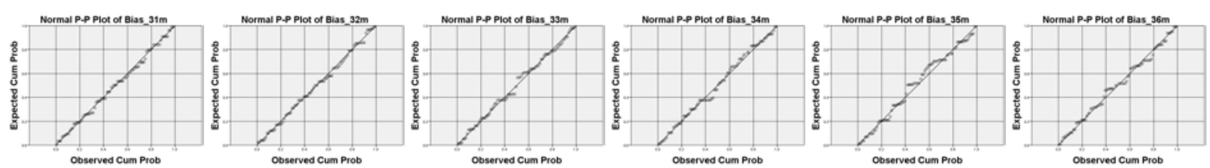
c)P-P distribution diagram results from 13 to 18 meter



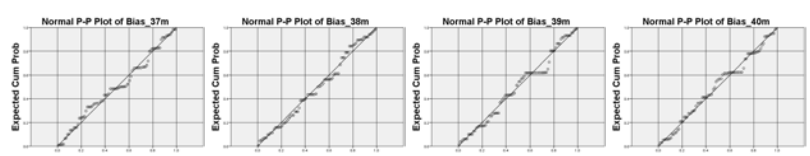
d)P-P distribution diagram results from 19 to 24 meter



e)P-P distribution diagram results from 25 to 30 meter



f)P-P distribution diagram results from 31 to 36 meter



g)P-P distribution diagram results from 37 to 40 meter

Fig.6-P-P normal distribution diagram results

The P-P test results showed that Vs test error basically obeyed the normal distribution. In this application, due to the mean is zero, it means that the test error obeyed standard normal distribution. In average, the standard deviation of for the total sites can be defined at 15%. This represent the average test bias of the three sites. By figured out this phenomenon, when we do the calculation in earthquake engineering we can use the test error probability as we want. For example, we can divide the shear-wave velocity test error into several sectors, such as ever 20% probability for one sector. Then we can estimate the probability that the test error may influence other relative parameters. That is the most useful conclusion of this research.

4 Discussion about the impact inspects

Three sites were all silty clay mixed with sand venues. The soil properties are likely the same and not far from each other. That is the reason why we can put the sites into together for analysis. The sites didn't have the loose grave collapse and shrinkage hole problems and also we have obtained the wave form imagines of the test, so that we discuss the some influence inspects according to the data. Although they have similar test error, but there are still something specific.

Surrounding Noise

The statistical result of each site showed that the environment noise affected the accuracy of the test error most obviously. Several buildings were under construction and the traffic was just 50 meters away near Site 1. Compared to Site 2 and 3(no significant noise around), the surrounding noise was much more obvious in Site 1. The data showed that the bias within two standard deviations on Site 1 was 82% and the same parameter was 90% in Site 2, 92% in Site 3. As mentioned before, there is more unreliable data in Site 1. After we checked out the wave form of the test, this phenomenon was due to the noise. When refers to the down-hoe test, it made the shear-wave form had vivid serrations and sometime caused the unfit of the first break of each layer. When refers to the P-S logging test, it made obvious wave shift between each layer. Also, if the wave data is analyzed manually, maybe the influence will be more obvious.

Data processing bias

When we analyze the shear-wave velocity, it is important to distinguish the first break shear-wave. Sometimes when we process the data we got the misfit of determine the beginning match point of the shear-wave. The data processing bias mainly comes from this. In the study we found that the data processing often have 10m/s to 20m/s misfit. This part can be called manmade test error.

Groundwater level

Groundwater level had no obvious affect on the test error of shear-wave velocity. In the round-robin test, we used two methods to get the shear-wave velocity: one was the down-hole method, the other was the P-S suspension logging test. Although they have totally different theory of the test, after we checked all the original shear-wave record, we found that the waves either below and above the water level is similar and with the same sharpness. So we reported that water level have no vivid influence to the travel time of the shear-wave.

Influence of the soil properties

In this experiment, the sites had similar soil properties. They are all silty clay mixed with sand. Although sand layers were at different depth of the site, but the test error was nearly the same. The transition from the lower to higher speed layer almost the same no matter what kind of the soil. We can draw the conclusion that the soil properties had no obvious influence to the test error.

In summary, the experimental principle of down-hole shear-wave velocity test is so simple. The main factor affecting the test error most is the judgment of the first-break point. If we ensure that we got the clear and accurate waveforms firstly and do the judgment work as precisely as possible, we can control the shear-wave velocity test error.

5 Conclusion

We finished 90 times round-robin shear-wave velocity tests on three typical engineering sites in Harbin China. By doing this we conducted a special study of the shear-wave test error. Eight test groups had been invited to completed the tests and showed off their own waveform. By analyzing the data, we proved that the test error obeyed the standard normal distribution and discussed the factors may affect the test error. We got the conclusions as followed.

1. Test error is almost the same at different depth. Standard deviation of the test error in these three sites is between 10% to 18%. According to the results, the average standard deviation of this round-robin test can be defined as 15%.

2. Standard normal distribution can be used to describe the shear-wave velocity test error based on the round-robin test.

3. Noise is the major fact which influenced the test error most. The reason is that the noise may influence the shear-wave form which will misleading the data analysis. Man-made mistake comes to the second and other inspects like the water level and the soil properties do not have obvious influence.

In summary, this paper presents the distribution of the shear wave velocity test error in the typical engineering field in China. Not only the research results will show a important phenomenon about the test error, but also will help the evaluation of the shear wave velocity in earthquake engineering.

6. Acknowledgements

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7. Copyrights

8. References

[1] Zhou Xiyuan, Wang Guangjun, Su Jingyu(1984):Site classification and average response spectra. *Chinese Journal of Geotechnical Engineering*, **6**(5), 59-68.

[2] Gao Yufeng, Liu Hanlong(2003):Study on shear wave velocities in expansive soils of Hefei , *Chinese Journal of Geotechnical Engineering*, **3**(25), 371-374.

[3] Liu Hongshuai, Zheng Tong, Qi Wenhao, Lan Jingyan(2010): Relationship between shear wave velocity and depth of conventional soils. *Chinese Journal of Geotechnical Engineering*, **7**(32), 1142-1149.

[4] Qiu Zhigang, Bo Jingshan, Luo Qifeng(2011): Statistical analysis of relationship between shear wave velocity and depth of soil. *World Earthquake Engineering*, **3**(27), 81-88

[5] Zhang Zhongli(2007): Statistical analysis of shear wave velocity in Construction sites. Master's Degree Thesis. *Research Associate, Institute of Engineering Mechanics, China Earthquake Administration.*

[6] Real, C. R(1988): *Turkey Flat, USA site effects test area: report 2, site characterization*

[7] D.S. Kim, H.J. Park, E.S. Bang(2013): Round Robin Test for Comparative Study of In-Situ Seismic Tests, *Geotechnical and Geophysical Site Characterization 4,* 1427-1434.

[8] Xia, J., R. D. Miller, C. B. Park, J. A. Hunter, J. B. Harris, J. Ivanov(2002): Comparing shear-wave velocity profiles inverted from multichannel surface wave with borehole measurements, *Soil Dyn.Earthq.*, **22**, 181–190.

[9] Asten M.W., D.M. Boore(2005): Comparison of shear-velocity profiles of unconsolidated sediments near the Coyote borehole(CCOC) measured with fourteen invasive and non-invasive methods, U.S. *Geol.Surv. Open-File Rept*. 2005-1169.

[10] Thompson E.M., L. G. Baise, R.E. Kayen(2007): Spatial correlationof shear-wave velocity in the San Francisco Bay area sediments, *SoilDyn. Earthq*., **27**, 144–152.

[11] Marosi K.T., D.R. Hiltunen(2004): Characterization of spectral analysis of surface waves shear wave velocity measurement uncertainty, *Geotech. Geoenviron.* **10**(130), 1034–1041.

[12] Thelen W. A., M.Clark, C.T.Lopez, C.Loughner, H. Park, J. B. Scott,S. B. Smith, B. Greschke, J. N. Louie(2006): A transect of 200 shallow shear-velocity profiles across the Los Angeles Basin, *Bull.Seismol. Soc*. **96**, 1055–1067.

[13] Boore D.M.(2006): Determining subsurface shear-wave velocities: a review, *3rd International Symposium on the Effect of Surface Geology on Seismic Motion, Grenoble, France.*

[14] Mahmoud N. Hussien, Mourad Karray(2015):Shear wave velocity as a geotechnical parameter: an overview， *Can. Geotech.,* **52**, 1-21.

[15] F. Garofalo, S. Foti, F. Hollender, P.Y. Bard, C. Cornou, B.R. Cox, M. Ohrnberger, D. Sicilia, M. Asten, G. Di Giulio, T. Forbriger, B. Guillier, K. Hayashi, A. Martin, S. Matsushima, D. Mercerat, V. Poggi, H. Yamanaka(2016): InterPACIFIC project: Comparison of invasive and non-invasive methods for seismic site characterization. Part I: Intra-comparison of surface wave methods, *Soil Dynamics and Earthquake Engineering*, **82**, 222-240.

[16] F. Garofalo, S. Foti, F. Hollender, P.Y. Bard, C. Cornou, B.R. Cox, A. Dechamp, M. Ohrnberger, V. Perron, D. Sicilia, D. Teague, C. Vergniault(2016): InterPACIFIC project: Comparison of invasive and non-invasive methods for seismic site characterization. Part II: Inter-comparison between surface-wave and borehole methods, *Soil Dynamics and Earthquake Engineering*, **82**, 241-254.

[17] William Navidi(2009): Principles of Statistics for Engineers and Scientists. *McGraw-Hill*