Methodology for Resilient Modulus Testing of Cohesionless Subgrades

SOHEIL NAZARIAN AND MANUEL FELIBERTI

Because more emphasis is being placed on incorporating resilient modulus testing in mechanistic pavement design, a reliable method for conducting the tests should be developed. The strengths and limitations of the resilient modulus testing procedure as applied to cohesionless subgrade soils are detailed in this paper. The overall objectives of this paper are to evaluate the accuracy of the resilient modulus test procedures, to modify the existing resilient modulus testing procedures as applied to granular materials, and to develop a more rigorous constitutive model for describing the results from resilient modulus tests. With a careful literature search in the areas of dynamic testing of soils as applied to transportation engineering, geotechnical engineering, and earthquake engineering, one can obtain a list of parameters that influence the results of cyclic tests (such as the resilient modulus tests). The compliance of the testing device, specimen preparation, level of deviatoric stress, and the sequence and number of loading schemes are the major parameters. Through extensive testing of synthetic specimens using state-of-the-art equipment, the accuracy, precision, and limitations of the procedure have been established. It was found that (a) a rigid system was required to minimize the compliance effects; (b) below a deviatoric stress of 2 psi, the results were questionable, and (c) the sequence of loading proposed by the AASHTO T-274 should be extensively modified. It was also found that the Strategic Highway Research Program protocol suggested for granular materials may result in excessive specimen disturbance. A newly developed procedure has been recommended herein. Given the level of emphasis in improving the resilient modulus testing procedure, it is reasonable to expect more advanced constitutive models representing the collected data. A new constitutive model was evaluated. The proposed model appears to be theoretically more accurate and describes the data more clearly.

In recent years, resilient modulus testing has gained tremendous popularity. This increased interest has been attributed to the new AASHTO design procedure adopted in 1986. In the new design procedure, the resilient modulus of subgrade soil is considered as one of the most important input parameters.

Since 1986, numerous research projects have focused on improving the laboratory procedure involved in conducting resilient modulus tests. A workshop was held at Oregon State University in 1989 to summarize the state of practice in resilient modulus testing. The major conclusions of the workshop were straightforward:

1. Using the resilient modulus as a design parameter would significantly improve the design procedures.
2. Available testing procedures were inadequate.
3. Resilient modulus testing devices needed modifications.
4. The constitutive models proposed were incomplete.

The Strategic Highway Research Program (SHRP) and many state agencies (such as those in Texas and Kentucky) have studied and suggested improved testing procedures and more advanced constitutive models.

Some of the inadequacies related to laboratory testing and modeling of resilient modulus tests conducted on cohesionless subgrades are addressed in this paper. Extensive laboratory tests were conducted to study the limitations of the existing methods proposed by SHRP and AASHTO using three synthetic specimens of known properties. An improved testing procedure was proposed that appears to induce the least amount of degradation and disturbance to the specimen. In addition, an improved constitutive model was proposed for cohesionless soils.

BACKGROUND

Many factors affect the resilient modulus of cohesionless subgrades. Resilient modulus is equivalent to dynamic modulus measured for geotechnical earthquake engineering projects. Cyclic triaxial tests (*1*) and resonant column tests (*2*) are two examples of tests typically used for this purpose. Dynamic modulus is the most important parameter used in this field. Naturally, a wealth of information is available, which cannot and should not be ignored.

Based on numerous laboratory tests, Hardin and Drnevich (*3*) proposed many parameters that affect the moduli of soils. They suggested that state of stress, void ratio, and strain amplitude are the main parameters affecting moduli measured in the laboratory.

Basically, as void ratio decreases, the dynamic modulus of soil increases. One of the most important factors that affects the dynamic modulus of soils is the applied confining pressure. Hardin and Drnevich (*3*) concluded that a linear logarithmic relationship exists between the modulus and the applied confining pressure.

The strain level has a significant effect on the dynamic modulus. Stokoe et al. (*4*) identified four ranges of strain amplitude. The thresholds are shown in Figure 1. The strain can be divided into four categories:

1. Small strains—also called elastic or low-amplitude strains, where linear behavior occurs;

S. Nazarian, Center for Geotechnical and Highway Materials Research, University of Texas at El Paso, El Paso, Tex. 79968. M. Feliberti, California Department of Transportation, Eureka, Calif. 95501.

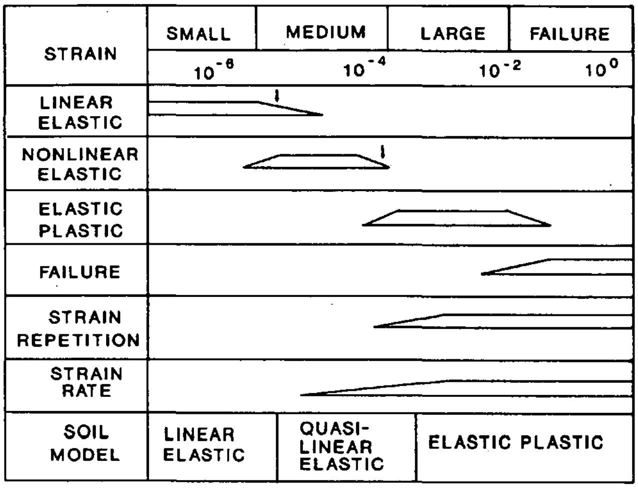

FIGURE 1 Soil behavior and associated strain ranges (*4*).

2. Medium strains—where nonlinear elastic behavior dominates this strain range;
3. Large strains—where significant plastic deformation occurs, but failure is not reached; and
4. Failure strains—all greater-than-large strains.

Two other threshold strains shown in the figure are the boundaries where the number of cycles of loads (denoted as strain repetition threshold) and strain rate of the load applied (denoted as strain rate threshold) become important in soils. The strain rate threshold roughly coincides with the limit of the small strains, and the strain repetition is located within medium strain level. As soon as the strain repetition threshold has passed, progressive failure will be imminent.

In pavement design, the strain levels are typically within ranges of small strains and medium strains. Higher strains will cause almost instantaneous rutting or fatigue cracking of the pavement.

Several constitutive models have been proposed for describing the results of resilient modulus tests. For cohesionless soils, the following relationship may be used:

$$M_R = k_1\theta^{k_2} \tag{1}$$

where

k_1 and k_2 = constants,
θ = bulk stress = $3\,\sigma_c + \sigma_d$,
σ_c = confining pressure, and
σ_d = deviatoric stress.

This relationship is extensively used for granular materials as recommended by AASHTO.

TESTING PROCEDURES

Recently much attention has been focused on conducting and implementing resilient modulus tests. As such, several new testing procedures and methodologies have been developed. Second to AASHTO, SHRP is the leading organization pursuing the implementation of resilient modulus tests. SHRP has suggested some improvement to the AASHTO T-274 procedure. Based on the type of material to be tested, both AASHTO and SHRP have proposed two separate procedures. Granular materials are tested differently than cohesive materials. The following sections present the AASHTO and SHRP procedures for testing cohesionless materials. An alternative procedure is also proposed.

The resilient modulus tests were performed with a closed-loop servo-valve system manufactured by MTS, Inc. The details of the equipment can be found in work by Feliberti et al. (*5*). An extremely rigid triaxial cell was used.

AASHTO Procedure

The AASHTO testing procedure is lengthy because it requires testing of the specimen under numerous stress states and loading conditions. There are 33 steps in this procedure. At each loading step, 200 cycles of load are applied. The resilient modulus is calculated from the results of the 200th cycle. The initial six steps, which are called conditioning steps, would presumably help the specimen to become more homogeneous. In other words, during the conditioning steps, any voids in the specimen are supposedly removed and it is hoped that a good contact between the specimen and load platens is achieved. Data are not collected during these steps. During this study, the six pretesting steps resulted in unrecoverable deterioration of many specimens before the actual testing. After the conditioning steps, the specimen is tested at five confining pressures, and at each confining pressure, increasing deviatoric stress is applied. The deviatoric stress ranges from 1 to 20 psi. During this study, a complete test on one specimen (including preparation of the specimen) required about 4.5 hr.

SHRP Procedure

Contrary to AASHTO's recommendation, SHRP requires only one conditioning step. The substantial decrease in the number of pretesting steps would certainly decrease the chances for specimen degradation or disturbance.

The actual test consists of 15 loading steps. The load is applied for 100 cycles with the 100th cycle being the cycle where the resilient modulus is calculated. The authors found this procedure easy to follow and perform. The test period for one specimen was approximately 2.5 hr because of fewer loading steps and fewer cycles of load. This procedure requires five confining pressures with deviatoric stresses from 3 to 40 psi.

The authors experienced one major problem with the SHRP procedure: the specimens were disturbed due to large deviatoric stresses applied at low confining pressures. These steps result in excessive deformation of specimens, especially if the specimen has a low modulus. During the authors' testing program, several specimens failed before completion of all the loading steps.

One advantage of the resilient modulus test is that it is a stage test. The specimen should not fail during testing, nor should its properties significantly alter between consecutive loading sequences. As such, the test had to be modified so that the specimen would not be subjected to high stress levels. A new loading sequence for cohesionless soils was developed to minimize the disturbance to a specimen during testing.

Proposed Procedure

In the AASHTO and SHRP methods, the confining pressure is kept constant and the deviatoric stress is varied. In this proposed method, the deviatoric stress is held constant while the confining pressure is increased.

The loading steps for the proposed procedure are shown in Table 1. The first row, where the loading sequence is 0, is the conditioning step. It is the same as for the SHRP method except that 50 cycles of load are applied. The rest of the 15 loading steps are run for 100 cycles. A complete test, including specimen preparation, takes approximately 2 hr. Three deviatoric stresses are used in this procedure. Five confining pressures are tested at each deviatoric stress. The confining pressures range from 3 to 20 psi. The fourth column specifies the number of load repetitions to apply at each loading step, and the fifth column indicates whether data are collected.

The proposed method was developed to minimize the disturbance to specimens during staged testing as observed with the SHRP procedure. The stress levels are much lower than both the AASHTO and SHRP procedures. The advantages of this testing procedure over others are demonstrated later.

EXPERIMENTAL RESULTS

Synthetic Specimens

Three synthetic specimens were tested before testing actual soil specimens. The synthetic specimens were composed of a two-component urethane elastomer resin (*6*). The three were named TU-700 (soft specimen), TU-900 (medium specimen), and TU-960 (hard specimen).

Stokoe et al. (*6*) extensively tested similar specimens using the static compression test and torsional resonant column test. Young's moduli obtained from the static compression tests for soft (TU-700), medium (TU-900), and hard (TU-960) specimens were 1,670, 6,550, and 32,300 psi, respectively. The Poisson's ratios were 0.48, 0.50, and 0.47 for the soft, medium, and hard specimens, respectively.

TABLE 1 Loading Sequence Proposed for Type 1 Soils

Loading Sequence	Deviatoric Stress, psi	Confining Pressure, psi	Number of Repetitions	Deformation Record(Y or N)
0	5	15	50	N
1	3	3	100	Y
2	3	6	100	Y
3	3	10	100	Y
4	3	15	100	Y
5	3	20	100	Y
6	6	3	100	Y
7	6	6	100	Y
8	6	10	100	Y
9	6	15	100	Y
10	6	20	100	Y
11	9	3	100	Y
12	9	6	100	Y
13	9	10	100	Y
14	9	15	100	Y
15	9	20	100	Y

Moduli obtained from the resonant column tests were also reported. Young's moduli for the soft, medium, and hard samples were 2,430, 10,070, and 52,000 psi, respectively. They attributed the difference in the numbers to the loading frequency. In other words, the elastomer specimens exhibited viscoelastic behavior.

In summary, through a rigorous series of laboratory testing, Stokoe et al. (*6*) demonstrated that the elastomer specimens were excellent tools for evaluating a resilient modulus device. Three correction factors had to be applied to each specimen before the accurate resilient modulus could be found. These three corrections compensated for (a) loading frequency, (b) testing temperature, and (c) mode of testing (torsional versus axial). The shear modulus of the elastomer specimens can be measured with an accuracy of 3 percent (*6*). All three specimens were approximately 2.8 in. in diameter and 6.5 in. in height.

An extensive amount of data was collected. Basically, each specimen was tested following the SHRP and AASHTO procedures. In addition, the proposed procedure was also evaluated. Tests were carried out securing the specimen to the platens with and without the hydrostone grouting mix.

There are several reasons for conducting such an extensive testing program. First, any incompatibility associated with the loading sequences could be found. Second, the specimen is subjected to numerous combinations of confining pressures and deviatoric stresses. Most tests were repeated at least three times. Although not shown here, in all cases the results were repeatable and demonstrated small deviations.

Typical results from resilient modulus tests on the medium specimen (TU-900) are discussed here. The results from the other two are included in Feliberti et al. (*5*).

The AASHTO and SHRP results for the granular (Type 1) testing procedures are summarized in Figures 2(*a*) and 2(*b*), respectively. The results from the two sets are similar. Much scatter in data is evident from the AASHTO procedure due to the numerous steps involving deviatoric stress levels of less than 2 psi. If the modulus corresponding to these stress levels is ignored, the results from the SHRP and AASHTO procedures are compatible. For both cases, the modulus is unaffected by the bulk stresses and is more or less constant.

The results from the proposed procedure are shown in Figure 2(*c*). The results and trends are similar to those obtained from the AASHTO and SHRP procedures. There is some scatter in the data because the tests were accidentally performed at deviatoric stresses of slightly less than 2 psi (instead of 3 psi).

The average modulus obtained from each testing procedure is summarized in Tables 2–4 for the soft material (TU-700), medium material (TU-900), and the hard material (TU-960), respectively. Also included in the tables are the standard deviation and coefficient of variation associated with each procedure.

The resilient modulus values for three elastomer specimens corrected for loading frequency, temperature, and mode of vibration were determined to be 2,318 psi, 9,794 psi, and 42,083 psi, respectively. (The synthetic specimens and their moduli were graciously provided by the University of Texas at Austin.) These specimens were subjected to similar tests,

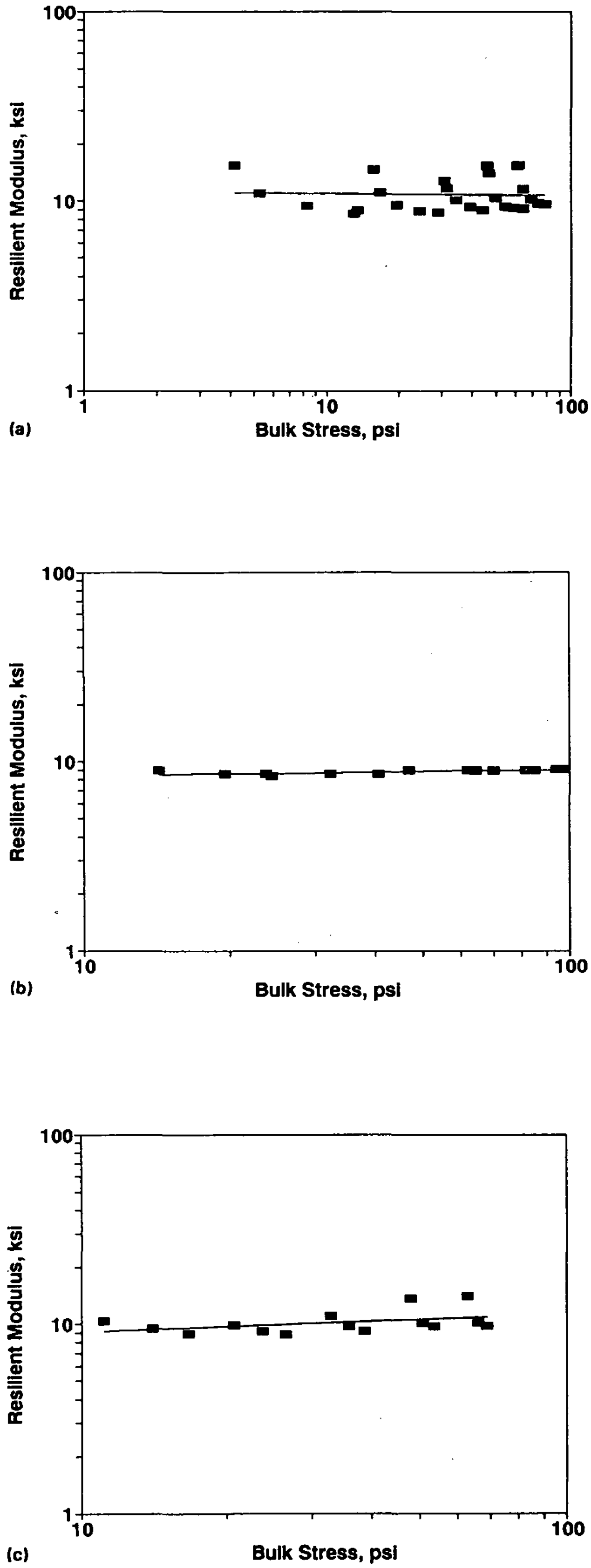

FIGURE 2 Variation in resilient modulus with bulk stress for TU-900 specimen: (*a*) AASHTO procedure; (*b*) SHRP procedure; (*c*) proposed procedure.

TABLE 2 Summary of Results from Tests on Soft Specimen (TU-700)

Testing Method	Hydrostone	Modulus (psi)	Standard Deviation (psi)	Coefficient of Variation (percent)	Percent Difference (percent)
SHRP	Y	2420	160	6.6	4.4
	N	2360	83	3.5	1.8
AASHTO with σ_d of	Y	2800	380	13.6	20.8
1 and 2 psi	N	2460	370	15.0	6.1
AASHTO without σ_d of	Y	2570	160	6.2	10.9
1 and 2 psi	N	2340	60	2.6	1.0
Proposed	Y	2390	190	8.0	3.1

Note: $Percent\ Difference = \dfrac{\text{Modulus from this Study - Modulus from Torsional Tests}}{\text{Modulus from Torsional Tests}}$

TABLE 3 Summary of Results from Tests on Medium Specimen (TU-900)

Testing Method	Hydrostone	Modulus (psi)	Standard Deviation (psi)	Coefficient of Variation (percent)	Percent Difference (percent)
SHRP	Y	8850	256	2.9	-9.6
	N	10140	610	6.0	3.5
AASHTO with σ_d of	Y	11060	2400	21.7	12.9
1 and 2 psi	N	10100	830	8.2	3.1
AASHTO without σ_d of	Y	9320	480	5.2	-4.8
1 and 2 psi	N	10150	410	4.0	3.6
Proposed	Y	9950	911	9.2	4.5

Note: $Percent\ Difference = \dfrac{\text{Modulus from this Study - Modulus from Torsional Tests}}{\text{Modulus from Torsional Tests}}$

TABLE 4 Summary of Results from Tests on Hard Specimen (TU-960)

Testing Method	Hydrostone	Modulus (psi)	Standard Deviation (psi)	Coefficient of Variation (percent)	Percent Difference (percent)
SHRP	Y	45700	1440	3.2	4.4
	N	N/A	N/A	N/A	N/A
AASHTO with σ_d of	Y	46270	3700	8.0	5.7
1 and 2 psi	N	38660	4780	12.4	-11.7
AASHTO without σ_d of	Y	46270	1050	2.3	5.7
1 and 2 psi	N	41260	3000	7.3	-5.7
Proposed	Y	44580	1260	2.8	1.9

Note: $Percent\ Difference = \dfrac{\text{Modulus from this Study - Modulus from Torsional Tests}}{\text{Modulus from Torsional Tests}}$

that is, torsional resonant column tests, reported by Stokoe et al. (*6*).

Average moduli from different testing procedures generally compare reasonably well with those measured using the torsional devices. For the soft specimen, the modulus varies from a minimum of 2,104 psi to a maximum of 2,800 psi. The device used in this study is unable to yield consistent results at deviatoric stresses of 1 and 2 psi. If the two AASHTO cases where the deviatoric stresses of 1 and 2 psi were considered were ignored, the lower and upper bounds would change to

2,104 psi and 2,606 psi, respectively. Similarly, for the medium specimens, the modulus varied between 8,850 psi and 10,150 psi, and for the hard specimens, between 39,860 psi and 46,270 psi. In almost all cases, the deviations in modulus from those determined from the torsional tests were within a 10 percent range.

The effects of the grouting of the specimens to the top and bottom platens were also studied. Tests were conducted on each specimen with and without applying the hydrostone mix. The addition of the grouting agent would ensure a good contact between the specimen and the platen. Precision machining was required to obtain flat surfaces necessary for performing the tests without the grouting agent. In general, the variation in results among the specimens grouted and those not grouted was about 10 percent. The variation was random. That is, in some cases, the grouted specimens yielded a higher modulus; and in other cases, the ungrouted specimens yielded a higher modulus. It seems that with the grout in place, moduli should be equal to or greater than those of ungrouted specimens. Although extremely unlikely, it is possible that the grout had not set completely before the tests were performed. This would account for some variations in the results. No reason other than random scatter in data can be found for this matter.

One advantage of grouting is that in some instances, the scatter in data decreases as judged by the coefficient of variation. Once again, favorable results shown here for ungrouted materials were possible after the ends of the specimens were precisely machined. It is important that the two ends be flat and parallel. Without this precision machining, practically any modulus value could be obtained depending on the setup.

The authors' conclusion is that as suggested by Pezo et al. (*7*), grouting the specimens is a good practice. However, for cohesionless materials, this may be infeasible because the grouting agent may flow inside the specimen. In that case, careful preparation of the specimen would result in satisfactory results.

Sand Specimens

The second phase of the testing program consisted of characterizing and testing a sand commonly found in El Paso, Texas. The properties of the sand and the development of the proposed method are described in this section.

The sand was first sieved with only the fraction passing through a #40 sieve and retained on a #60 sieve used for testing. This sand was extensively used by De Lara Rico (*8*). The maximum and minimum unit weight for the sand were 106.9 pcf and 93.2 pcf, respectively. Based on the gradation, the sand was classified as A-3 by AASHTO soil classification and as SP in the Unified Soil Classification System.

Of the 13 specimens, 3 were tested at a relative density (r_d) of 100 percent following the SHRP testing protocol, 7 were tested at a r_d of 100 percent, and 3 were tested at a r_d of 70 percent. The proposed procedure, not the AASHTO procedure, was followed for testing in this study.

The first three specimens, with a r_d of 100 percent, were tested to evaluate the proposed procedure. Each specimen was tested at different deviatoric stresses to analyze the effects of deviatoric stress on specimen degradation. A more detailed testing program was conducted and can be found in work by Feliberti et al. (*5*). Those results, which are not discussed here for the sake of brevity, support the conclusions drawn here.

A typical variation in modulus with bulk stress for a sand specimen using the SHRP protocol is illustrated in Figure 3. The scatter in the data is relatively small. Generally, the modulus increases with the bulk stress. The data are clustered into five groups corresponding to the five different confining pressures.

Repeatability was checked by testing three specimens. The results were the same for the first confining pressure. However, when the specimen was subsequently tested at a different confining pressure, the results obtained were erratic. This indicated possible degradation of the specimen at high deviatoric stresses, suggesting that the SHRP procedure might require some modifications.

Under the proposed procedure, the variation in resilient modulus with bulk stress for a sand specimen at 100 percent r_d (similar to the specimen tested with the SHRP procedure) at deviatoric stresses 3, 6, and 9 psi is shown in Figure 4(*a*). The scatter in data is relatively smaller than that obtained from the SHRP method. The modulus increases linearly with bulk stress. To demonstrate that the specimen degradation is minimal, two other specimens were tested. The first specimen was tested at deviatoric stresses of 6 and 9 psi [Figure 4(*b*)], and the final specimen was tested at only the deviatoric stress of 9 psi (Figure 5). The modulus values at the deviatoric of 9 psi for the three specimens compare closely, as shown in Figure 5. In the authors' experience, this degree of repeatability cannot be achieved with the SHRP procedure. For the first level of confining pressures, similar results could be achieved. However, for the subsequent confining pressures, the moduli would be lower, and the results would not be repeatable.

After repeatability of results with the proposed procedure was established, two other specimens were tested at 100 percent r_d. These results were similar to those presented in Figure 4(*a*). Three tests yielded almost identical results, with moduli

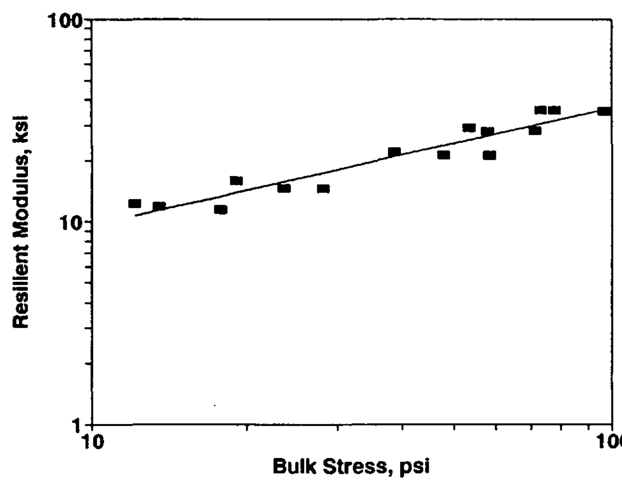

FIGURE 3 Variation in resilient modulus with bulk stress for a sand specimen at a relative density of 100 percent following SHRP procedure.

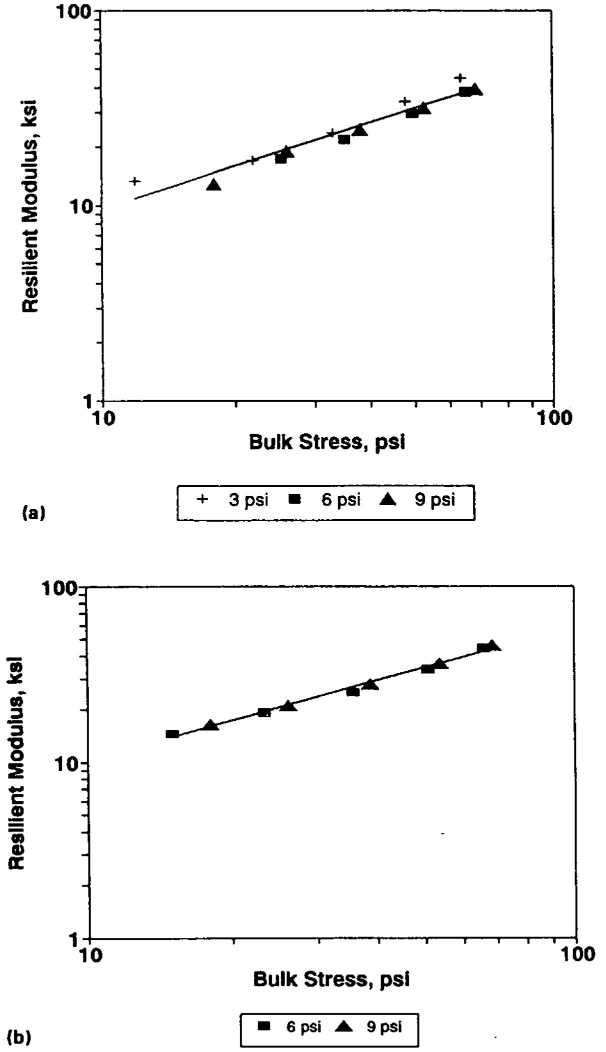

FIGURE 4 Variation in resilient modulus with bulk stress for a sand specimen at a relative density of 100 percent following the proposed procedure: (*a*) tested at three confining pressures; (*b*) tested at two confining pressures.

from the last being slightly lower. In any case, the variation in modulus was quite small among the four specimens.

Finally, three specimens were tested at a relative density of 70 percent. Variation in modulus with bulk stress for one representative specimen at this relative density is shown in Figure 6. The resilient modulus increases with an increase in bulk stress. However, some scatter in the data is evident. The moduli from the three tests were within 10 percent of each other.

CONSTITUTIVE MODELS

The constitutive model proposed by SHRP or AASHTO is presented in Equation 1. For granular materials, both SHRP and AASHTO recommend a relationship between resilient modulus (M_R) and bulk stress (θ).

For the sandy material tested, using a least-squares best fit method, Equation 1 yields R-squared values from 0.78 to 0.98

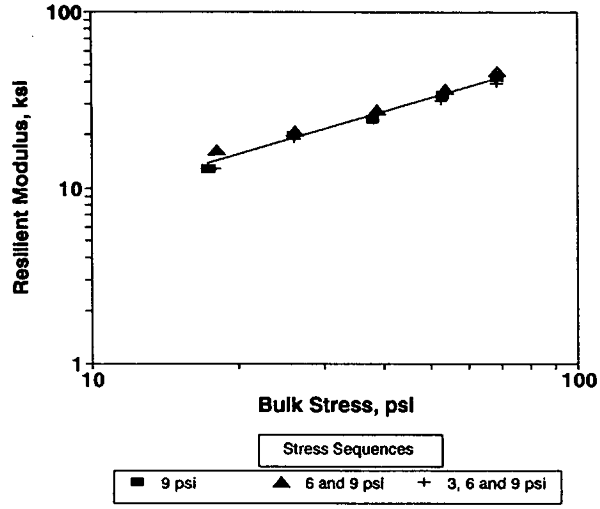

FIGURE 5 Comparison of variation in resilient modulus with bulk stress for three sand specimens tested at different deviatoric stresses following proposed procedure.

with an average of about 0.85. The average values for k_1 and k_2 were 0.399 and 0.581, respectively. Given the recent emphasis on improving the experimental aspects of resilient modulus tests, such a level of correlation may not be adequate.

As mentioned before, for a given soil, Hardin and Drnevich (*3*) found that two parameters significantly contribute to the stiffness (modulus) of soils. These two parameters (besides void ratio) are the state of stress and the strain level. As such, the models proposed by AASHTO and SHRP directly consider the effects of the state of stress (bulk stress) but ignore the effects of strain amplitude. One model studied that considers both of these factors is in the form

$$M_R = 10^{k_1} \theta^{k_2} \varepsilon^{k_3} \qquad (2)$$

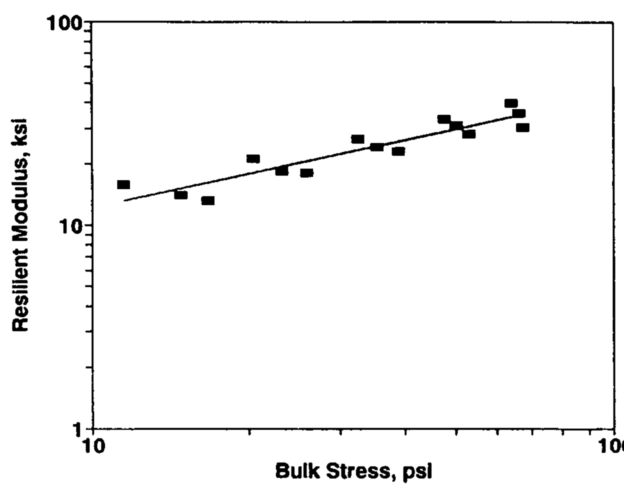

FIGURE 6 Variation in resilient modulus with bulk stress for a sand specimen at a relative density of 70 percent following proposed procedure.

where k_1, k_2, and k_3 are the material constants to be obtained from tests performed on a given soil. When the model was applied to the resilient moduli from different tests, the R-squared values were generally above 0.95, except for some isolated cases, with an average of 0.98. The average values for k_1, k_2, and k_3 were -0.131, 0.668, and -0.128, respectively. The difference between the measured modulus and calculated modulus from the AASHTO/SHRP equation for the granular material (Figure 3) is shown in Figure 7(*a*). The figure corresponds to the modulus values obtained from three similar specimens tested at a relative density of 100 percent. There is a significant difference between the actual data and the modeled data. The deviation between the two is as high as 45 percent, but it is typically within 30 percent. The similar plot for the same data, but for the model presented in Equation 2, is shown in Figure 7(*b*). The measured and calculated moduli compare better, and the scatter is usually less than 15 percent.

It should be mentioned that the tests in this study yielded strain amplitudes in the range of 10^{-3} to 10^{-1} percent. Therefore, the above discussion is pertinent only in this range of strains.

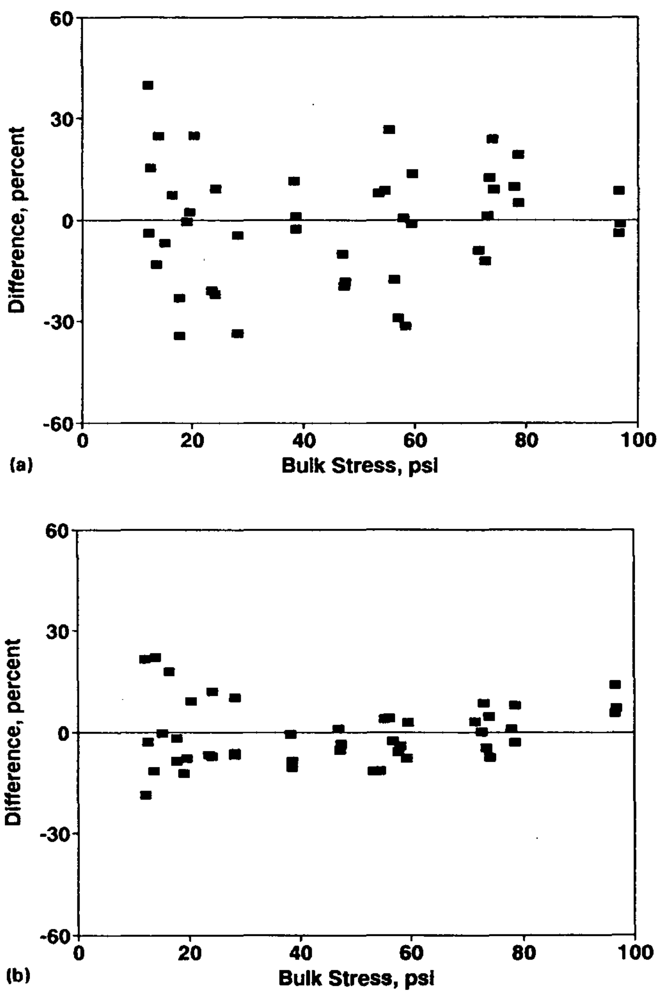

FIGURE 7 Typical variation in percent difference between measured and modeled moduli: (*a*) AASHTO/SHRP model; (*b*) proposed constitutive model.

SUMMARY AND CONCLUSIONS

This paper evaluates the resilient modulus testing procedure for cohesionless materials and reviews the state-of-the-art for obtaining and interpreting resilient modulus data. The initial testing procedure was proposed by AASHTO and then improved by SHRP. These two approaches are evaluated. In addition, a new testing procedure for granular materials is proposed and evaluated.

On the basis of this study, the following conclusions can be drawn:

1. The AASHTO procedure for resilient modulus testing is inadequate.
2. The SHRP protocol for testing granular (Type 1) soils induces specimen disturbance during the first level of confining pressure.
3. The new procedure proposed here for testing granular materials appears to minimize specimen degradation and disturbance.
4. The models proposed by AASHTO may be incomplete for sands.
5. A general constitutive model based on considering both state of stress and strain amplitude, which seems more appropriate for describing the behavior of the material tested, is introduced.

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