New Method to Compute Reload and Unload Pressuremeter Moduli

Roger A. Failmezger
In-situ Soil Testing L.C., Morattico, Virginia, USA

Gabriel Sedran
In-Depth Geotechnical Inc., Hamilton, Ontario, Canada

ABSTRACT: Multiple cycles of unload-reload stress-strain loops during pressuremeter testing results in increasing values of the corresponding unload and reload moduli (U-R moduli). When plotting U-R moduli vs. strain a linear relationship is identified. The corresponding coefficients of linear regression, R^2, are typically greater than 0.95. Moduli values for unload-reload loops near the yield stress, typically the first loop, do not follow those best fit lines and are typically about 40% lower. U-R moduli can be determined at any radial strain using these best-fit equations, which can be used for finite element modeling. In-situ PMT test data from three case studies are presented demonstrating these relationships. A new approach to compute U-R moduli as a function of strain level is presented.

RÉSUMÉ : Plusieurs cycles de déchargement-rechargement contrainte / déformation boucles pendant pressiomètre, résultats des tests en augmentant les valeurs des correspondant décharger et recharger les modules (modules de U-R). Lors du traçage des modules U-R vs souche une relation linéaire est identifiée. Les coefficients correspondants de la régression linéaire, R^2, sont généralement supérieures à 0,95. Valeurs de modules pour les lignes de déchargement-rechargement près de la limite d'élasticité, généralement la première boucle, ne suivent pas ces lignes fit mieux et sont typiquement environ 40 % plus bas. Modules de U-R peuvent être déterminées à n'importe quelle contrainte radiale à l'aide de ces équations ajustées, ce qui peuvent être utilisées pour la modélisation par éléments finis. Données de test in-situ PMT de trois études de cas sont présentées démontrant ces relations. Une nouvelle approche pour calculer les modules U-R comme une fonction du niveau de la souche est présentée.

KEYWORDS: in-situ testing; pressuremeter; reload and unload moduli; finite element analyses.

1 INTRODUCTION

There is an important class of geotechnical applications where construction and structural loading results in a soil mass deforming in a quasi-elastic manner. The installation of a secant wall, followed by staged excavations, and staged tieback stressing, for instance, belong to this class of quasi-elastic stress-strain problem. The soil mass, in general, is subjected to a stress regime which necessarily includes unloading and reloading. Most of the deformations occur under quasi-elastic, small-strain conditions.

Geotechnical practioners are increasingly analyzing this type of applications with the help of advanced finite element (FE) models together with material properties of soils inferred from in-situ testing such as pressuremeter (PMT).

The development of robust and user-friendly FE models has made the tasks of geotechnical engineers much easier than it used to be a few years ago. Finding accurate material properties for the soil still remains a critical task.

PMT testing is one of the very few in-situ tests which provides high quality stress-strain data related to the soil's response to loading. Reliable soil parameters can be inferred from this stress-strain data. More importantly, PMT test data provides information related to a) in-situ stresses; b) deformations properties; and c) strength parameters.

This paper focuses on the properties necessary to analyze deformations ocurring during quasi-elastic, unload-reload conditions as they occur during installation of a shoring system, as noted above. For such geotechnical applications, the unload-reload moduli (U-R moduli) are often times considered as the governing soil parameters controlling deformations during construction and structural loading of the bearing strata.

The general aspects of deformation paramaters obtained from PMT testing can be reviewed in the classic literature on the subject, see for instance, Baguelin et al.(1978), Briaud (1992), Clarke (1995), and others. The particular topic of U-R moduli are discussed in this paper. A detailed reference to the topic was presented by Combarieu et al. (2001).

Briaud et al. (1983) presented a discussion of U-R cycles on different soils using strain-controlled PMT testing. In part of their discussions, and based on one U-R load cycle, they provided a hyperbolic stress-strain model from which values of the U-R moduli could be inferred at any strain level. However, the presented test data corresponded to PMT tests conducted on soils above groundwater table, and with particular attention to pavement-subgrade structures.

This paper presents a new method to obtaing relevant U-R moduli from PMT testing for soils both above and below groundwater level. This paper further examines the effect of multiple unload-reload stress-strain loops and provides modelling parameters. Often, engineers perform only one unload-reload loop near the end of the elastic behavior and the beginning of the plastic behavior of the pressuremeter test. The authors performed additional unload-reload loops in the plastic region at higher levels of radial strains. Moduli values from these loops form linear relationships with radial strain while the moduli values from the first unload-reload loop near the yield stress were significantly lower than these linear relationships.

2 EQUIPMENT

To establish unload-reload moduli relationships, the engineer must accurately measure pressures and volumes during the pressuremeter test. We chose a TEXAM pressuremeter because volume measurements are accurate to ±0.01 cm^3. With a digital pressure gauge, pressure readings were accurate to ± 1 kPa.

A Roctest N-size probe was used for the measurements. The initial radius was 36.9 mm and its length was 500 mm, giving an initial volume of 2139 cm^3. The volumes were increased at typically 40 cm^3 steps and the resulting pressures were measured about every 15 seconds. After expanding the probe, the pressure at the control unit exceeded the pressure in the probe. We recorded the pressure 5 seconds later so that the pressures at the control unit and probe could equalize.

For the unload-reload loops, the volume was decreased 20 cm^3 and then increased 20 cm^3. With these volume changes, the pressure was reduced to about 50% of its previous value and then increased to slightly less than pre-loop value.

3 ANALYSES

For both the unload and reload cycles, the authors plotted the moduli values versus the corrected radial strain. The corrected radial strain equaled the average radial strain for that cycle minus the radial strain for the probe to contact the borehole sidewalls.

From these plots, they discovered excellent linear relationships for modulus versus strain for all the values in the plastic zone. The equations to compute reload and unload modulus are as follows:

$$E_{r\varepsilon} = E_{r0} + (m_r)(\varepsilon) \quad \text{, and} \qquad (1)$$
$$E_{u\varepsilon} = E_{u0} + (m_u)(\varepsilon) \quad \text{, where} \qquad (2)$$

$E_{r\varepsilon}$ is the reload modulus at a chosen radial strain;
E_{r0} is the reload modulus at zero radial strain;
m_r is the slope of the modulus-strain line for reload;
ε is the radial strain;
$E_{u\varepsilon}$ is the unload modulus at a chosen radial strain;
E_{u0} is the unload modulus at zero radial strain; and
m_u is the slope of the modulus-strain line for unload.

In-situ test practitioners commonly perform an unload-reload cycle near the yield point where the soil transitions from elastic behavior to plastic behavior. The authors also performed cycle near the the yield point and for this cycle designated the reload modulus as E_{r1} and the unload modulus as E_{u1}. These moduli values were about 40% less than values computed from the linear relationships for the other moduli in the plastic behavior zone.

4 TEST DATA

Prebored pressuremeter tests were performed at three sites with different geologies. As shown on Figure 1, a typical test sequence consisted of inflating the pressuremeter in equal volume increments to the yield point at the end of the elastic behavior, an unload-reload cycle, a creep holding test for 10 minutes at the next volume increment, and four or five more unload-reload cycles at increasing volume increments of 200 cm^3 and a final unload near the limit pressure.

Pressuremeter tubing stiffens during unloading due to the material properties of rubber. For a system calibration in a thick walled steel pipe, the authors applied 0.5 MPa pressure increments to 5 MPa, unloaded to 2.5 MPa, and reloaded to 5 MPa. The volume at 2.5 MPa during unloading was more than the initial loading volume at 2.5 MPa. Thus the volume for the unload measurement was corrected following the procedure discussed by Tucker and Briaud (1990).

When the authors plotted reload and unload moduli versus the corrected radial strain, they observed the values for the first loop near the yield stress were significantly less than the other values in the plastic behavior. The reload and unload moduli in the plastic zone had linear relationships with radial strain. The slopes of those lines for both the unload and reload moduli tended to parallel each other with the unload line having higher values than the reload line. The coefficients of correlation for these lines generally exceeded 0.95, confirming strong relationships. Figure 2 shows a typical plot of unload and reload moduli versus radial strain.

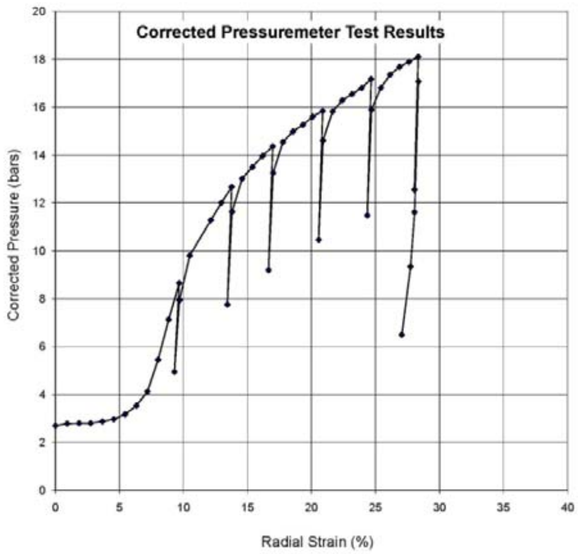


Figure 1. PMT test with six U-R cycles

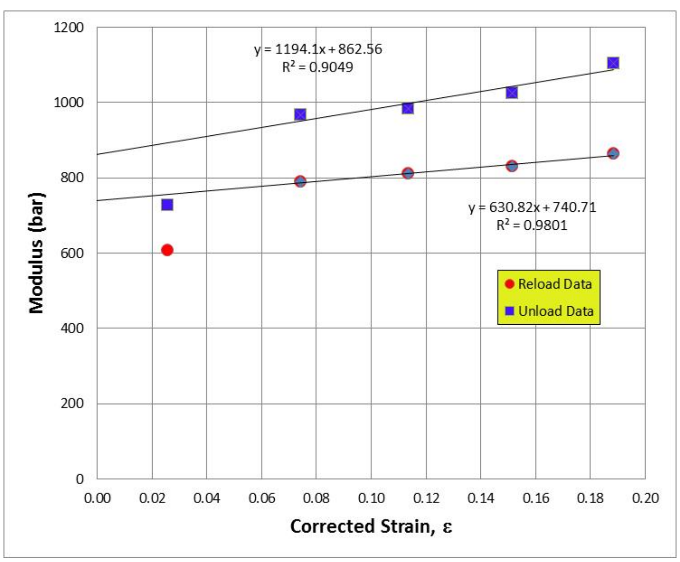


Figure 2. U-R moduli versus radial strain.

4.1 Miocene Aged Fine Grained Soil in Forestville, Site in Maryland

Thirteen pressuremeter tests were performed in a borehole from 6.4 to 25.2 meters at approximately 1.6 meter depth intervals. Laboratory index tests were performed on soil samples collected from an offset boring to complete soil classification. Approximately 90% of the soil was finer than the Sieve #100. The soil was classified as silty or clayey fine sand or fine sandy clay or silt. The soil is over-consolidated and sensitive.

4.2 Residual Soil of Piedmont Formation in Howard County, Site in Maryland

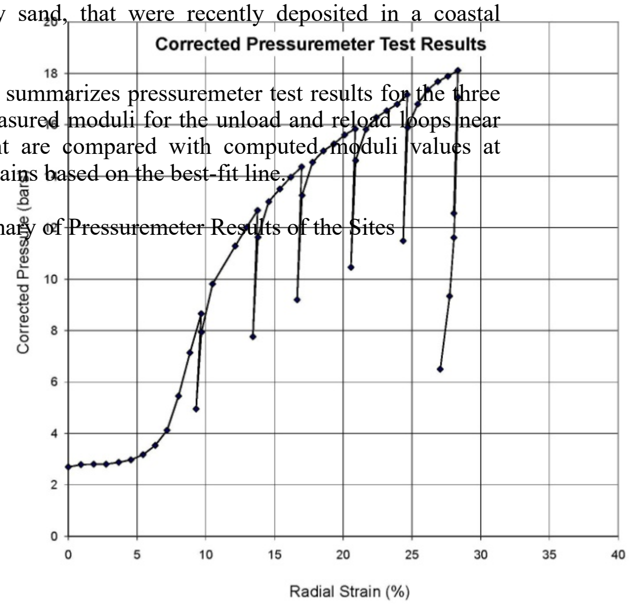
Five pressuremeter tests were performed in two boreholes at depths from 1.8 to 7.1 meters. The site consisted of residual soil from chemical weathering of the parent micaceous schist rock. The soil was more weathered near the surface and less weathered at 7.5 meters. The soil classified as a silty fine sand.

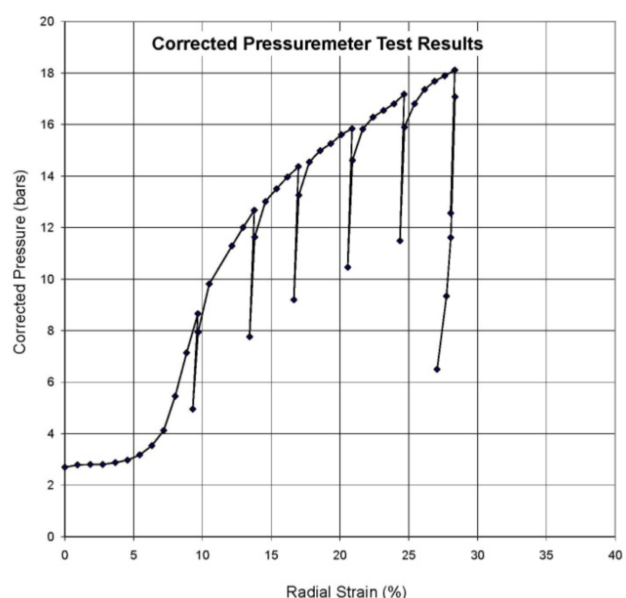
4.3 Recent Coastal Sand and Clay Deposits in Corpus Christi, Site in Texas

Six presssuremeter tests were performed in one borehole from 2.0 to 23.8 meters. The soils were interbedded layers of sand and clay, primarily sand, that were recently deposited in a coastal setting.

Table 1 below summarizes pressuremeter test results for the three sites. The measured moduli for the unload and reload loops near the yield point are compared with computed moduli values at those radial strains based on the best-fit line.

Table 1. Summary of Pressuremeter Results of the Sites





Miocene Aged Fine Grained Soil -- Forestville, Maryland

Depth	P_l	E_o	Er_1 (bar)		Er_0			Eu_1 (bar)		Eu_0		
(m)	(bar)	(bar)	measured	computed	(bar)	m_r	r^2	measured	computed	(bar)	m_u	r^2
6.40	7.5	119	584	724	662	1737	0.995	668	835	761	2088	0.988
8.38	8.2	93	473	609	541	2534	0.998	578	701	619	3041	1.000
9.91	7.7	90	297	490	474	838	0.994	406	631	605	1368	0.991
11.43	9.5	125	492	589	553	1087	0.988	620	760	718	1304	0.985
12.95	11.5	175	606	757	741	631	0.980	726	894	863	1194	0.905
14.48	14.0	257	737	814	797	494	0.938	889	1009	983	764	0.937
16.00	14.8	266	844	948	895	1850	0.988	1070	1198	1136	2164	0.998
17.53	11.0	115	461	639	582	1925	0.994	671	812	736	2591	0.983
19.05	14.0	244	693	814	792	799	0.999	962	1036	993	1594	0.869
20.57	16.5	284	1023	1167	1116	2045	0.992	1301	1470	1377	3619	0.993
22.10	12.0	197	696	730	704	944	0.951	875	920	882	1392	0.791
23.62	19.0	277	1123	1407	1275	3772	0.997	1454	1761	1564	5636	0.953
25.15	22.0	263	1114	1342	1172	5692	0.995	1433	1866	1647	7340	0.978

Residual Soil -- Howard County, Maryland

Depth	P_l	E_o	Er_1 (bar)		Er_0			Eu_1 (bar)		Eu_0		
(m)	(bar)	(bar)	measured	computed	(bar)	m_r	r^2	measured	computed	(bar)	m_u	r^2
1.77	6.5	46	301	475	370	1940	0.956	379	562	429	2459	0.936
4.39	13.0	125	649	1264	1204	2020	0.962	799	1449	1373	2602	0.982
1.55	4.7	63	436	595	553	758	0.953	522	694	643	904	0.959
3.60	18.5	286	1464	2669	2620	1953	0.988	1668	2934	2934	3273	0.967
7.07	35.0	625	3751	5357	5138	5468	0.823	4349	6439	6090	8699	0.977

Coastal Deposits -- Corpus Christi, Texas

Depth	P_l	E_o	Er_1 (bar)		Er_0			Eu_1 (bar)		Eu_0		
(m)	(bar)	(bar)	measured	computed	(bar)	m_r	r^2	measured	computed	(bar)	m_u	r^2
1.98	13.0	177	563	696	593	3578	0.969	666	773	623	5218	0.974
3.20	7.5	54	394	428	180	3682	1.000	442	449	120	4887	0.999
7.77	9.5	218	429	476	429	1094	0.979	599	596	549	1098	0.996
15.09	28.0	367	1273	1744	1589	6492	0.990	1598	2281	2109	7212	0.977
18.35	39.0	589	2291	3836	3648	6637	0.857	2780	4507	4192	11176	0.958
23.77	45.0	448	2117	3226	2921	11831	0.919	2833	3873	3456	16225	0.948

5 CONCLUSIONS

- When multiple unload-reload stress-strain loops are performed in the plastic behavior zone with a pressuremeter test, linear relationships of unload and reload moduli versus radial strain can be established. The moduli values increase with increasing radial strain.

- The exception to these relationships are the moduli values from an unload-reload loop near the yield stress where the soil transitions from elastic to plastic behavior state. These measured moduli values are about 40% lower than moduli computed from the linear relationships.

6 REFERENCES

Baguelin F., Jezequel J.F. and Shields D.H. 1978. The pressuremeter and foundation engineering. TransTech Publications.

Briaud J.L., Lytton R.L., and Hung J-T. 1983. Obtaining moduli from cyclic pressuremeter tests. Journal of Geotechnical Engineering, Vol. 109, No.5, pp 657-665.

Briaud J.L. 1992. The pressuremeter. Balkema.

Clarke B.G. 1995. Pressuremeters in geotechnical design. Taylor & Francis.

Combarieu O. and Canépa Y. 2001. The unload-reloadpressuremeter test. Bulletin des laboratoires des pontes et chaussées – 233 – July-August 2001 - Réf. 4381 – pp 37-67.

Tucker Larry M. and Briaud Jean-Louis 1990. User's Manual for Presred. Civil Engineering Department Texas A&M University