Reasons for CAPWAPC Underprediction and Overprediction

by

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1. Introduction

CAPWAPC is probably the most accurate analysis available for the separation and calculation of dynamic and static resistance forces from dynamic records resisting the pile motion induced by a hammer blow. However, we encounter situations where static load tests and CAPWAPC analyses yield differing results. Thus, in the majority of cases, CAPWAPC "underpredicts", i.e., it is possible to apply much higher static loads than dynamically predicted. Dangerous capacity overpredictions seldom occur; fortunately, they can be avoided. In this paper the sources of data misinterpretations will be discussed. Several contributors to the 1990 PDA Users Days will deal with the same subject.

When static and dynamic results do not agree, critics of dynamic methods are quick to point out that "dynamic methods do not work". Others blame the lack of care in the preparation and performance of static tests. We know that both dynamic and static tests "work" but neither test is easy and care must be taken in test preparation, performance and finally the interpretation of results.

For those not too familiar with the CAPWAP signal matching process, the reason for data misinterpretations seems obvious: Lack of Uniqueness. However, no argument would be further from the truth. Recalculations performed after a static load test usually do not allow us to simply produce a new and "better" solution with a better match quality. Let's face it, the static and dynamic observations occasionally do not agree by significant amounts.

2. A GENERAL LOOK AT CAPWAP

The basic assumption of CAPWAP may be described as follows. While the pile is moving into the ground, static and dynamic (damping) resistance forces build up and decay in a manner which is vividly linked to pile displacements and velocities (Figure 1). It is assumed that the same relationships will hold true whether or not the pile penetrates into the ground

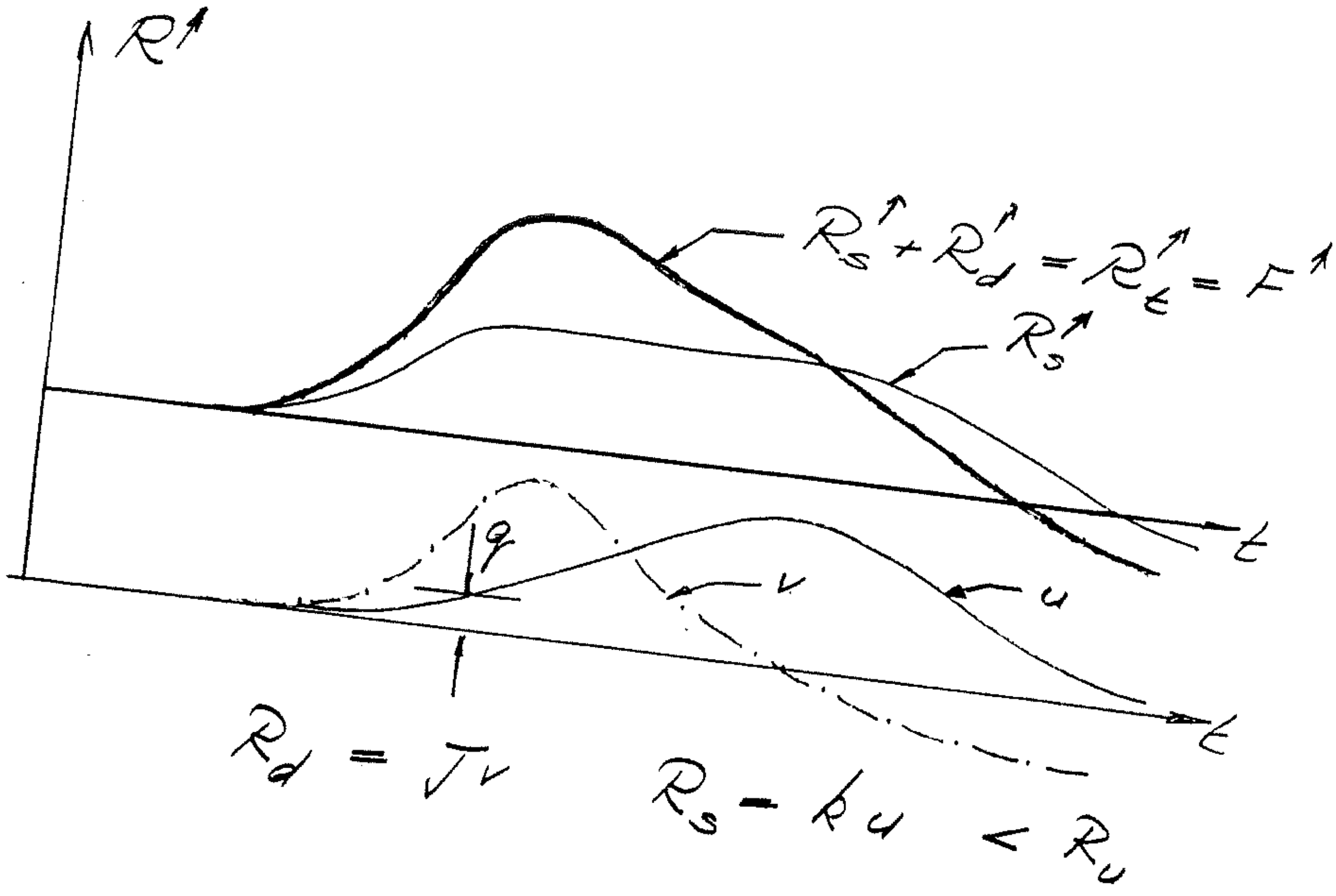

Figure 1: The Basic CAPWAPC Matching Process

at high or low speeds. CAPWAPC can only work where velocities and displacements vary during the event[1]. (Of course, this sounds silly since the pile is first at rest, then moves quickly and finally rebounds). If pile velocities were constant, so would be the assumed damping forces and therefore a separation from static forces would not be possible.

[1]The RS1 Case Method only considers the damping and velocity maxima. So does the so-called SIMBAT Method (or so it seems from a rather meager description).

Our matching process is therefore dependent on the more or less arbitrary velocity history. If damping resistance forces and pile velocities were truly linearly related, then the shape of the pile velocity curve would not matter. But are they linearly related? Will a rebound velocity of magnitude -1 m/s producing the same (but oppositely directed) damping force as a downward directed velocity of +1 m/s?

Laboratory studies to date only indicate that the **maxima** of the damping and velocity histories are **not** linearly related. True, Smith damping models really establish a non-linear relationship. In general, CAPWAP shows that the Smith damping model is not proper and that the truly linear viscous model works better. Particularly in the late record portion, the static resistance has unloaded and therefore the Smith damping force vanish and only viscous damping can produce the obviously dampened piling behavior.[2]

Does it matter whether we choose the proper damping model? Apparently yes. We have seen cases where the CAPWAP matching process required unusually high damping factors. Applying lower more commonly encountered damping factors would not have produced a satisfactory match. No other single soil parameter has as powerful an effect on the match quality and capacity result as the damping factor.

3. Classification of Problem Cases

Overprediction

Soils Exhibiting <u>Relaxation</u> (Shales). For all piles driven into shales, local experience or static testing is a must. Restrike is testing not always successful, especially if wait time is only a day or two. It is also very important to choose only the first high energy blow for analysis.

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[2]Since it is sometimes necessary to maintain small toe damping when static toe resistance is small, the Smith approach is invaluable. A 1990 option allows the user to choose a toe damping model which behaves according to Smith until full static activation and viscously in the later analysis (OPdt=2).

Soils Exhibiting Creep (Shales, Decomposed Rock, Others?). Initially high capacities decay under or cannot sustain long term loads. Quick static tests may be as misleading as dynamic tests. Local experience is required.

Soils Exhibiting Strain Softening (Soft Silts, Clays, others?). Local Experience is Necessary. For low driving energies (high blow counts) predictions are usually adequate.

Soils Exhibiting Negative Pore Water Pressures (Fine Sands and Silts of High Density). Restrike testing is usually successful; assure meaningful results from first high energy blow (warm hammer).

Excessive Test Energies. Errors are introduced if pile sets per blow are large. Pile displacements may then exceed those of the failure definition. Hammer forces are high compared to static resistance values (prediction error is perhaps a percentage of impact force). Insufficient velocity variation will result and, therefore, what appears to be static resistance, may actually be damping.

Underprediction

Sensitive Soils, particularly clays may loose all of their static strength under dynamic loading due to a change in the soil's structure. (This is not a true pore water pressure effect). Their set-up factor may be as high as infinity. Static strength is regained with time. Sometimes very little waiting time is necessary for a regain of most of the pile strength. The necessary waiting times depend on the cause of loss of capacity.

Soils Subject to Increased Pore Water Pressures. It is well known that pore water pressures increase in fine grained soils (where they cannot dissipate quickly) during pile driving. In addition to clay, usually we think of silts as being fine grained; however, even fine sands sometimes seem to behave similarly. The increased pore water pressure causes a reduction in effective stresses and therefore lower frictional resistances during driving. After pile driving ceases the pore water pressures decrease more or less rapidly depending on permeability and the soil regains strength. Apparently, this effect more commonly occurs along the skin than at the toe. Restrike tests can eliminate this error source, since pore water pressures increase only relatively slowly with continued driving causing further displacement of water during restriking (not during a hammer blow). Waiting periods between driving and restriking may vary between an hour and 6 weeks; they must consider the speed of pore water pressure changes.

Soil Fatigue. This is really not very different from strength losses due to a change in the soil structure or in the effective horizontal stress. It was described for overconsolidated clays whose soil-pile interface becomes smoother and smoother with increasing number of hammer blows. Time will reduce this effect and restriking therefore reduces the potential error.

Soil Loosening. This is also an effect which set-up will correct. It occurs in probably all soil types. The soil loosening may cause a reduction in horizontal stresses and/or reduced density. It is caused by the unavoidable horizontal pile motions (pile whipping, Poisson's effect) and by voids created by plugs in open profiles or oversize pile shoes or extra large closure plates for pipe piles. Most soils have the ability to firm up around the pile after driving due to equalizing of soil pressures and restrikes are therefore usually successful.

Liquefaction. We often overlook or ignore this possibility. If the sand or sandy gravel is of low density and submerged, then the dynamics of the moving pile may liquefy the soil, i.e. the soil loses its strength. Liquefaction

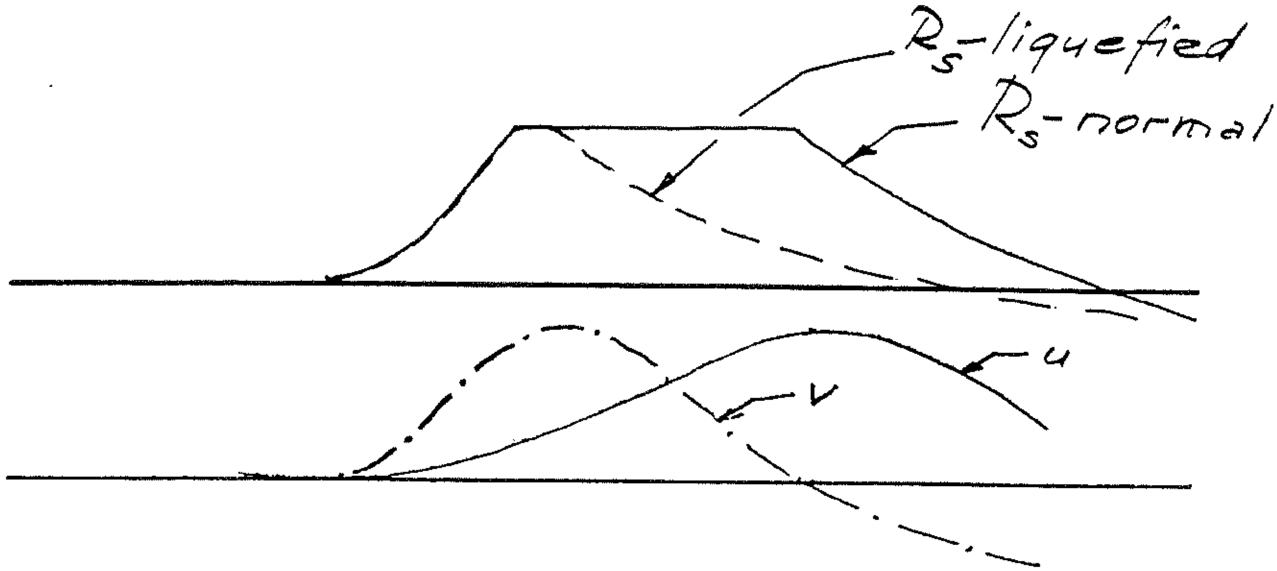


Figure 2: Static resistance, Pile Velocity and Displacement for Liquefying Soil

is known to occur during earthquakes and during the installation of piles using steady state vibrations. Preliminary indications are that the soil has its full static strength driving the hammer below the soil loses strength within a short time period as soil grains start rapid movements thereby losing their intergranular normal and friction forces. The static resistance vs. time relationship then appears to be similar to damping resistance (Figure 2). Since liquefaction occurs **during** the blow, restriking does not avoid underprediction. One clue to the occurrence of liquefaction are low blow counts. (As described in the next paragraph, pore water pressure increases would have the same effect on blow counts during driving, however, during restriking the effect of lost resistance then becomes apparent).

High Blow Counts or Small Permanent Sets per Blow. Note that temporary sets can be relatively high and yet the soil has not been fully tested to its

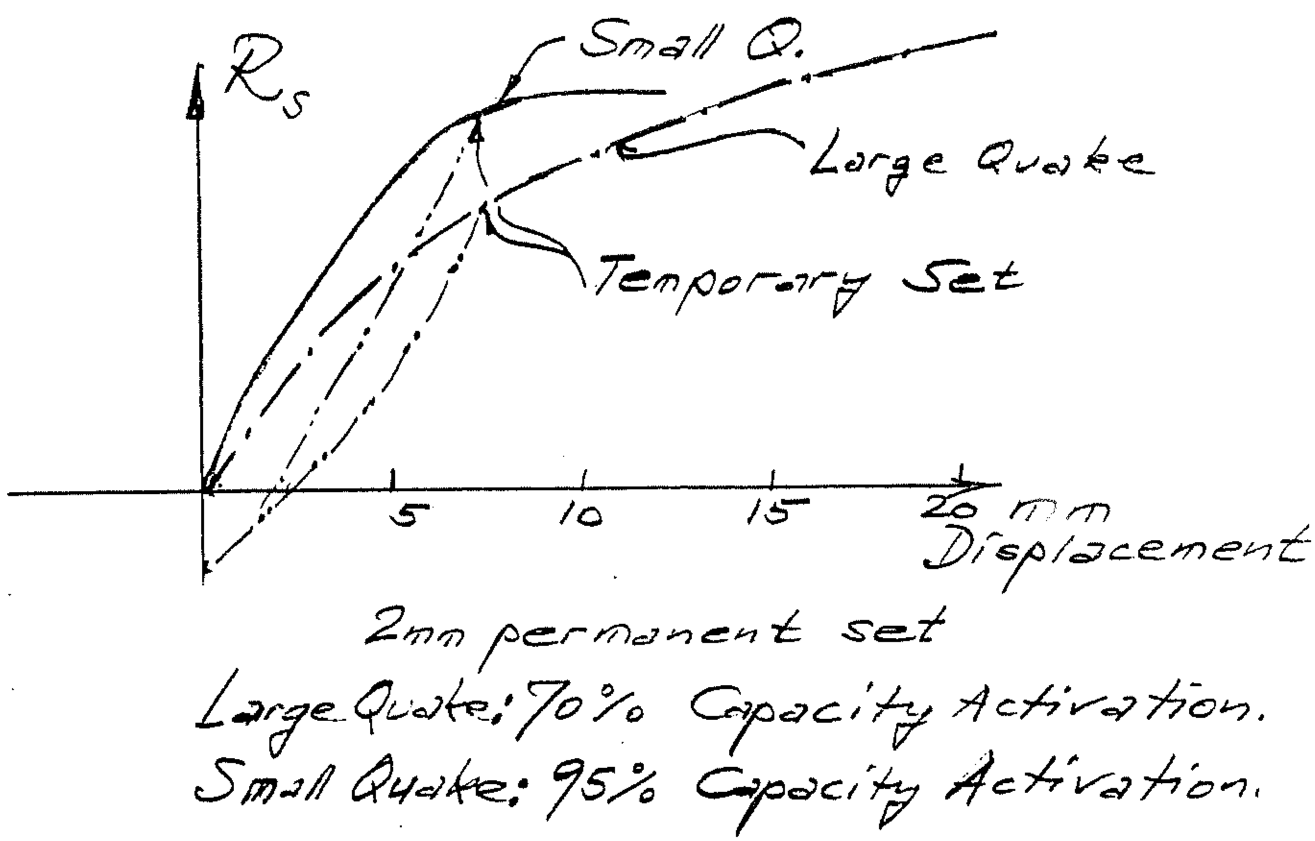


Figure 3: Load-Set Curves for Partial Activation

ultimate strength (Figure 3). This cause for underprediction is rather common. Remedies include: (a) use a bigger hammer or a higher drop height; (b) test both at end of driving and during restriking and find maxima of friction and end bearing. They may be combined to yield the total available bearing capacity. If you use (b) then, it is then extremely important to assure that a toe relaxation did not occur and that skin friction and end bearing at the pile toe were well distinguished. If you use this procedure, the restrike blow count **must** be very high.

Different Static and Dynamic Failure Modes - Plug. This is the most frustrating cause of underprediction. It occurs in relatively dense granular soils on open profile piles like open end pipes or H-piles. One hypothesis is discussed. During driving the pore water pressures increase such that friction is reduced to a point where a plug does not form. In the static case the plug sticks and generates a high end bearing. It is possible that the plug sticks for a short time in the beginning of the hammer blow and then slides **during** the blow. Then the force exerted by the plug onto the pile would be active for only an initial short time period. It would therefore be similar to and interpreted as damping. There doesn't seem to be a sure remedy except a limitation of damping in the analysis.

Different Static and Dynamic Failure Modes - Internal Friction (inside the pipe or between the flanges). A suddenly applied force (due to resistance) on the internal soil column will cause a wave to propagate in that medium. It will travel slower than in the pile, however, it will travel fast enough to cause a relatively quick decay of the resistance effect. If the internal soil column does not shear then the force effect will be proportional to acceleration and therefore associated with a dynamic resistance. Again, the best remedy is probably limiting the damping factors in the CAPWAP analysis.

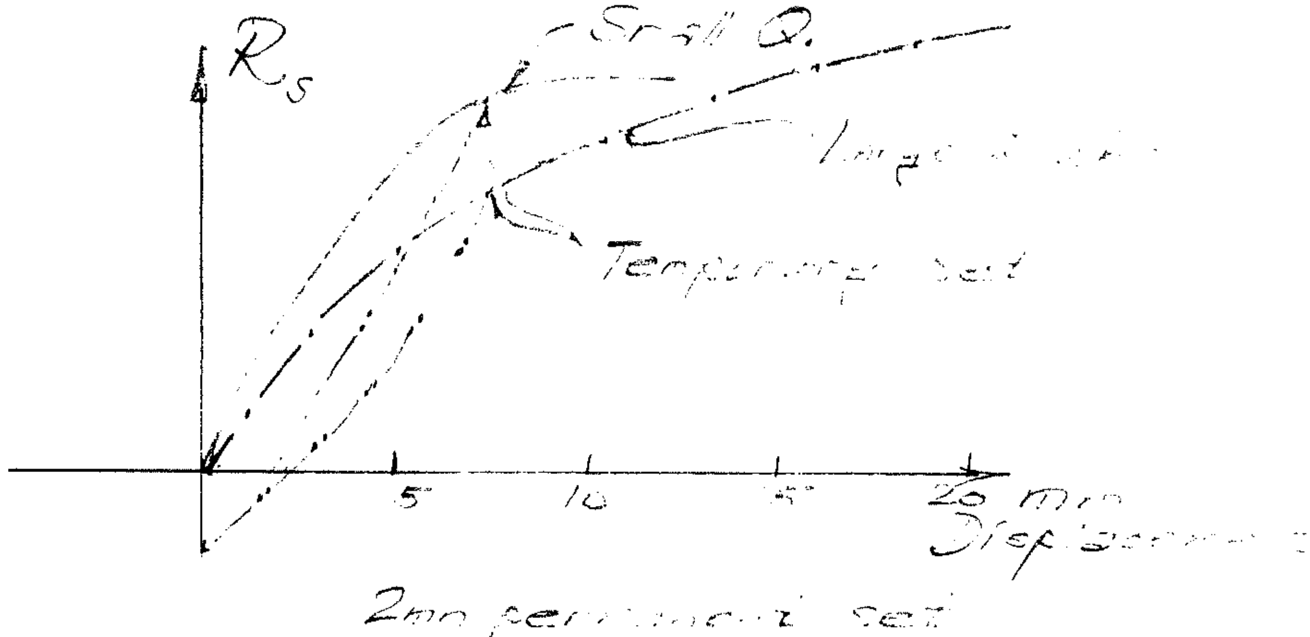
Radiation Damping. This source of underprediction errors is probably always negligible when the pile moves relative to the soil for a distance greater than the quake. However, for small pile displacements, relative to the quake, a wave is generated which travels trough the soil. The force exerted by the soil onto the pile is therefore dependent on the pile velocity and the resistance is interpreted as damping. The remedy is the application of radiation models (SKda, MSkn, BTda, MToe) or limited damping.

CONCLUSIONS

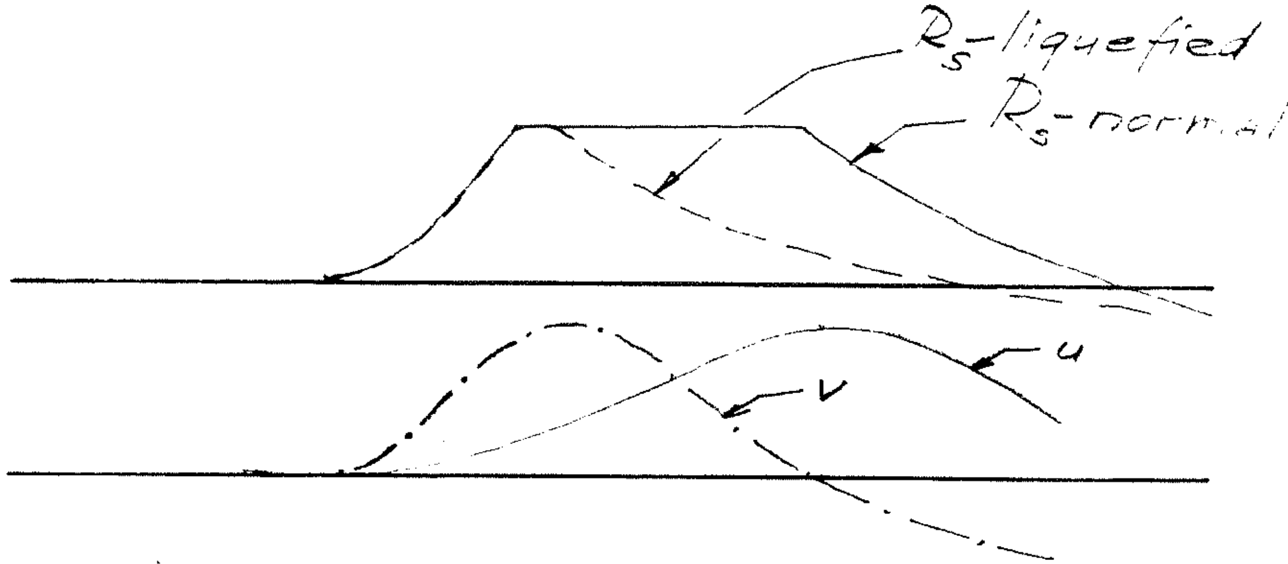
The list of problems compiled in this paper may not be complete. There may be additional reasons for inaccurate capacity predictions by CAPWAP. There may also be different remedies. It is suggested that we update this list as we learn more about the dynamics of pile driving.

Some dynamic testing reveals the capacity at the time of testing, restrike are considered the single best solution to obtaining good correlation and many of the aobve problems are solved by this solution. In some of the mentioned cases, remedies are suggested.

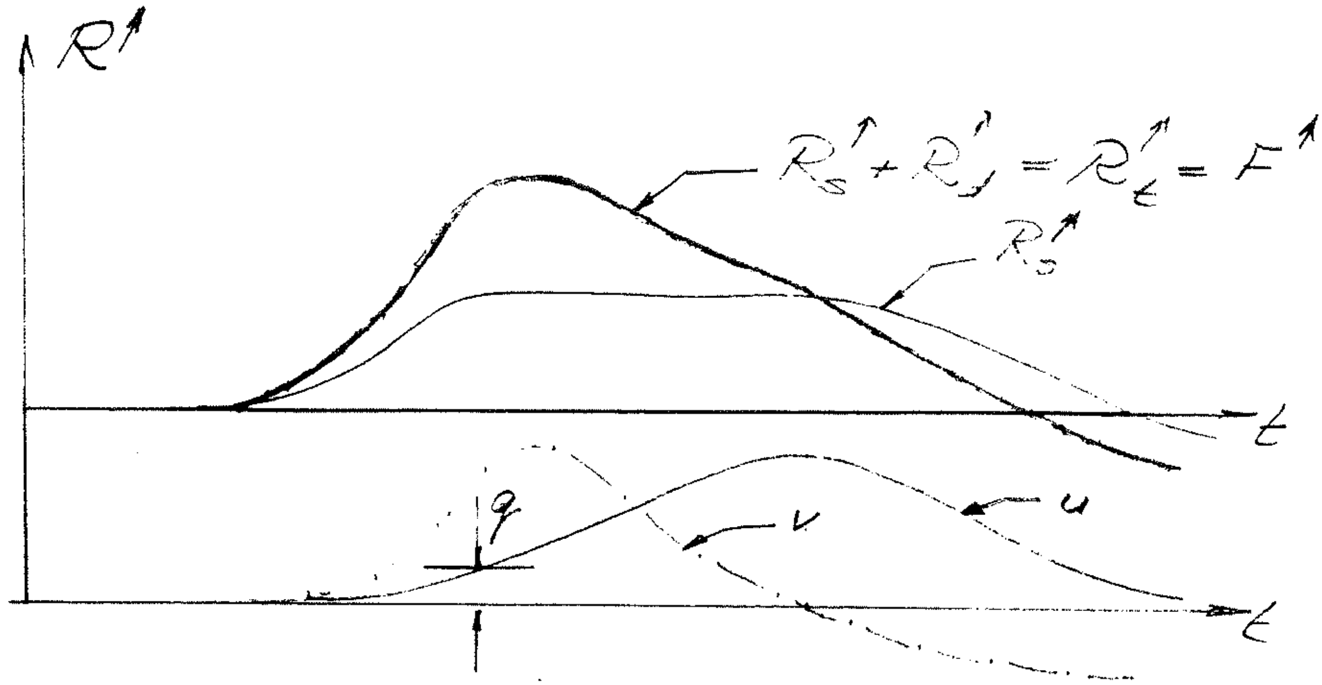
Ideally, all dynamic tests for capacity would be performed during restrike after a few days wait and that the set per blow be moderate.



Large Quake: 70% Capacity Activation.
Small Quake: 95% Capacity Activation.



Rs-liquefied
Rs-normal
u
v



$R_d = Jv \quad R_s = ku < R_u$

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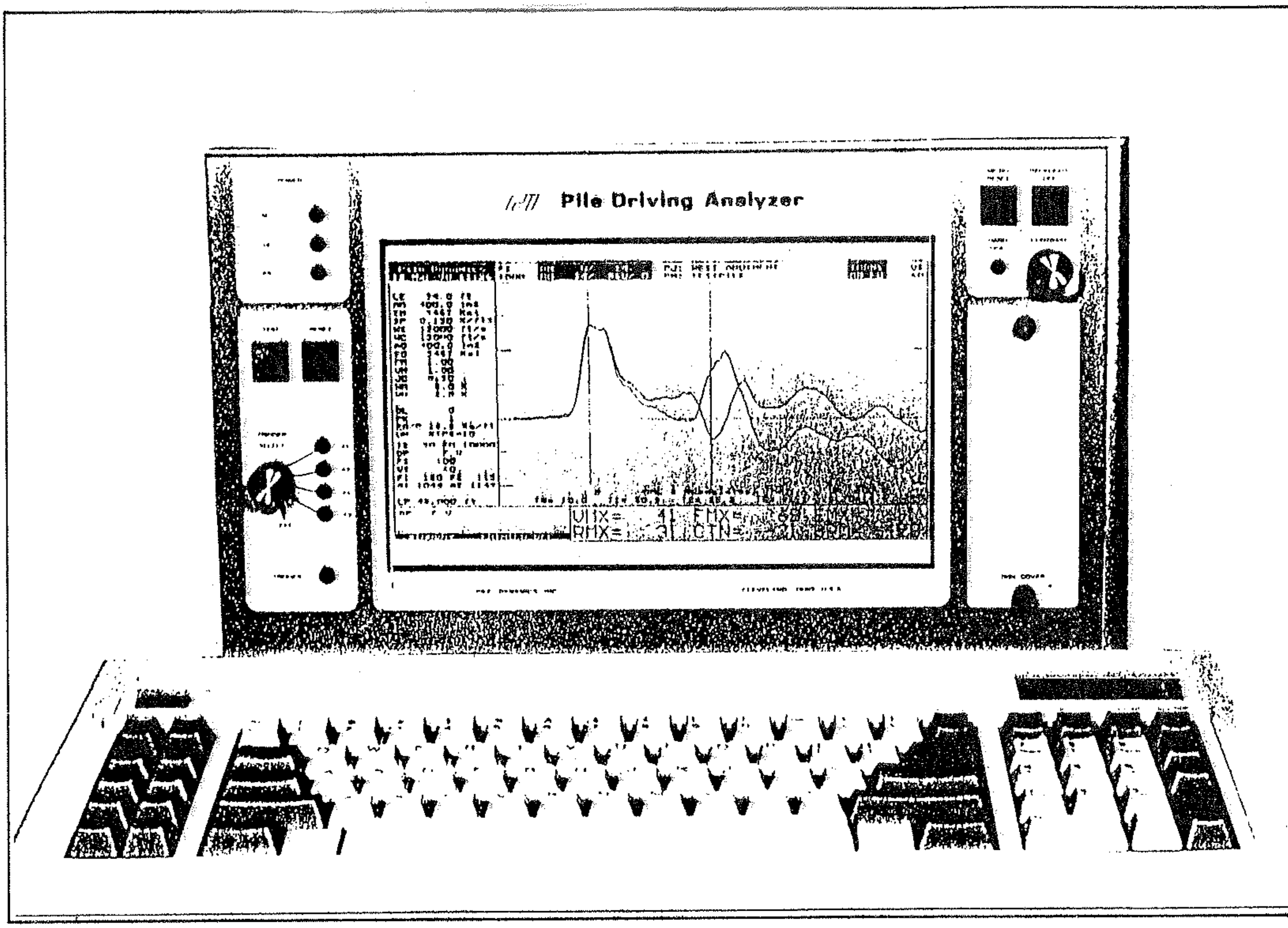

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