Fellenius releases wave equation

(Lecture notes from Deep Foundations Institute symposium held in Montreal on September 21, 1983 by Bengt Fellenius.)

MONTREAL -- The advent of the wave equation analysis was a quantum leap in modern foundation engineering. For the first time, the dull complex of pile driving could be considered. That is, velocity dependent aspect (damping), soil deformation characteristics, soil resistance (bearing capacity), resistance distribution (shaft and toe), hammer efficiency, cushion and capblock properties, etc. The mathematical model and procedures used are naturally a simplification of the reality, but accurate enough to be representative. In contrast, the dynamic formulae are fundamentally incorrect and only accidentally do the results of dynamic formulae resemble reality.

The use of dynamic formulae can be likened with the ancient method of sacrificial birds and basing decisions on the colour and shape of the birds' intestines. In fact, the use of bird intestines is preferred to dynamic formulae on the condition that the bird be shot and studied on site. Then, some real factors might influence the interpretations at least subconsciously.

However, while the wave equation is theortetically correct, when used without factual data the results are only qualitatively correct, not quantitatively. Each input datum is really a variable with a certain range of possible values. As there are many input data, the combined effect is that the results (for instance, a bearing graph) are only somewhere in the neighborhood of the quantitatively correct value. Therefore, we should never just be satisfied with one analysis (computer run), but use several runs trying to fork in the most probable conditions by using ranges of values. The results are then represented not as one well-defined curve, but as representative areas or bands.

The attached bearing graph (Fig. 1) shows an example of the recommended way of presenting wave equation results (WEAP). For this actual case, a back calculated project, a range of "refusals" had been obtained. By means of a WEAP analysis, the potential ultimate capacity of the piles were calculated as a function of the penetration resistance (blow-count). Note, that the band approach increases the range of potential capacity. As indicated, there is a wider and narrower width of the confidence band affecting the precision of the results.

Occasionally, the bearing graph can be paired with other experience information and "engineering judgement" and suffice for answer to the problem at hand. Usually, though, once one has realized the band necessity of the wave equation analysis, one must improve the accuracy of the results, because **THE WAVE EQUATION DOES NOT GIVE SINGLE LINE OR SIMPLE ANSWERS, AND IT IS A TOOL THAT CANNOT BE USED ALONE.**

The full power of the wave equation analysis is first realized when combined with dynamic monitoring of the pile during driving. Dynamic monitoring was developed in the USA by Dr. G. Goble and co-workers in the early seventies. It has since been accepted, adopted really, all over the world (as often happens, the full acceptance has been slower in coming in the States. The old reference to the prophet in his homeland is true, it seems). The dynamic monitoring consists in principle of clipping gauges onto the head of the pile to measure and record force and velocity induced in the pile by the impact. (There are numerous papers describing the actual system).

The results are usually presented in the form of "wave traces," which show the measured force and velocity drawn against time. (See Fig. 2) At first, force and velocity are proportional by the so called accoustic impedence, a material constant (equal to AE/c, the product of cross sectional area and elastic modulus over the wave progation velocity). Therefore, when plotted to scales with the ratio of the impedence, force and velocity plot on top of one another. When the strain wave travels down the pile meeting the soil, soil resistance will cause reflections of strain which travel back up the pile. These will result in an increase of the stress at the measuring point and a simultaneous decrease of velocity (the pile slows down), visible as a separation of the two curves. The greater the separation, the greater the resistance. At the pile end, if there is no toe resistance, a reflected tensile wave will result, which will be measured at the gauges as a loss of stress and an increase of velocity, that is, the force trace dips and the velocity pace peaks.

The above is illustrated in Figure 2 showing traces taken from the driving of a 140-feet 18-inch octagonal concrete pile. Conventionally, the force scale is

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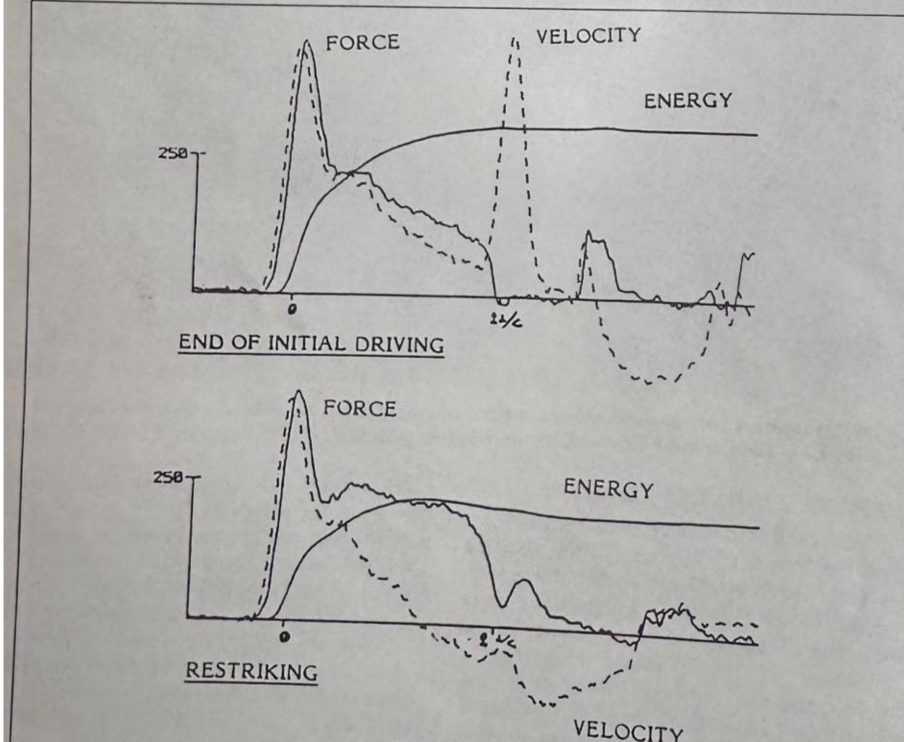

FIGURE 3

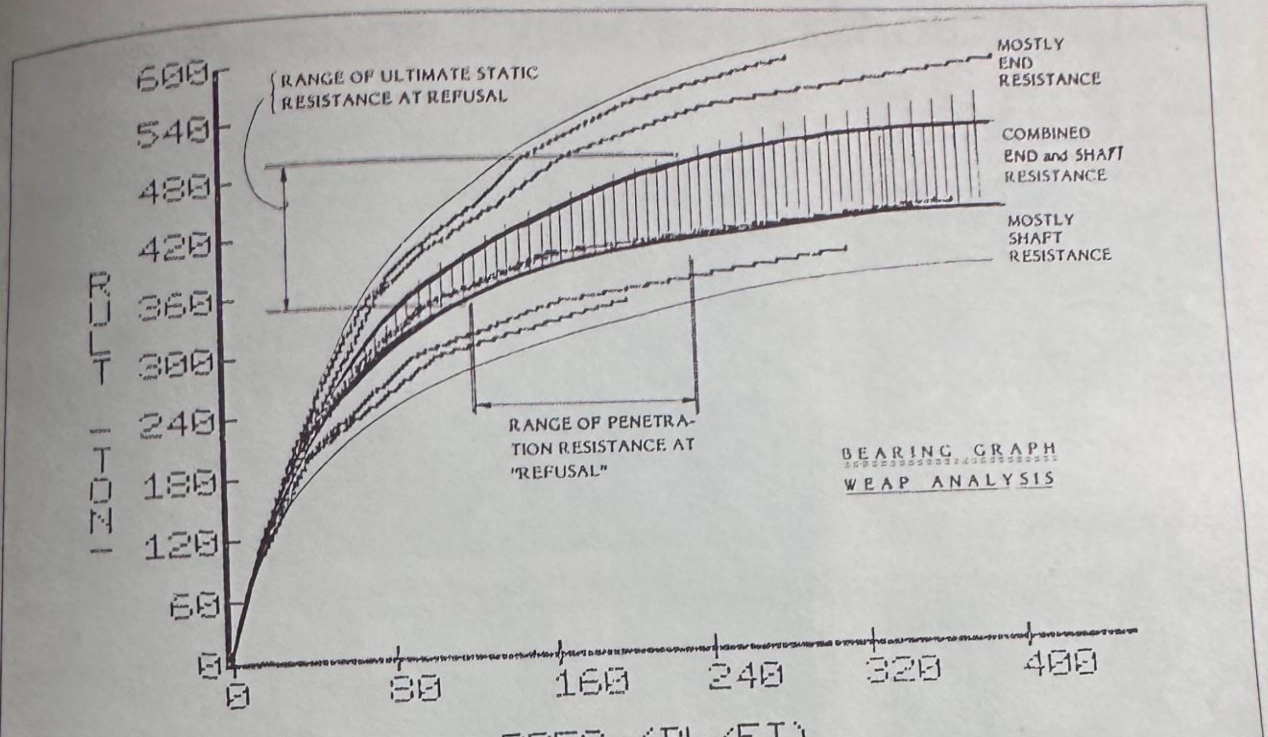

FIGURE 1

(Continued from P. 2)

given in units of L/C, that is, the time it takes for the strain wave to travel the length of the pile. At 2 L/C, therefore, the traces show the reflections originating from the pile toe. The peak at zero time, zero L/C, is defined as impact because the wave action force is transmitted to the pile before this time, as well as after. The graph shows traces from easy driving at a depth of 78 feet and when approaching refusal at 95 feet. The small separation of the force and velocity traces indicate that only little shaft resistance is occurring. The velocity peak at 2 L/C in the upper set of traces indicates that there is no or little resistance at the pile toe. The lower set show, in contrast, a small force peak indicating the presence of some toe resistance.

The visual study of the wave traces provides very important information to the engineer performing the monitoring in the field. Blowsby blow is displayed as the pile is driven. The data are routinely stored on a recorder and can be played back in the office for renewed study.

Figure 3 shows traces taken from a pile at the end of initial driving and at restrictions. The force and velocity traces have been supplemented with traces of measured energy. It should be obvious also for the inexperienced that the pile has been subjected to a capacity increase due to soil set-up, although the [illegible]formed with a smaller force and energy. The tremendous value of having such records in an actual case are evident.

The data can be treated analytically, of course. The two traces, force and velocity are mutually independent records. By taking one trace, say the velocity, as an input to a wave equation computer program called CAPWAP, a

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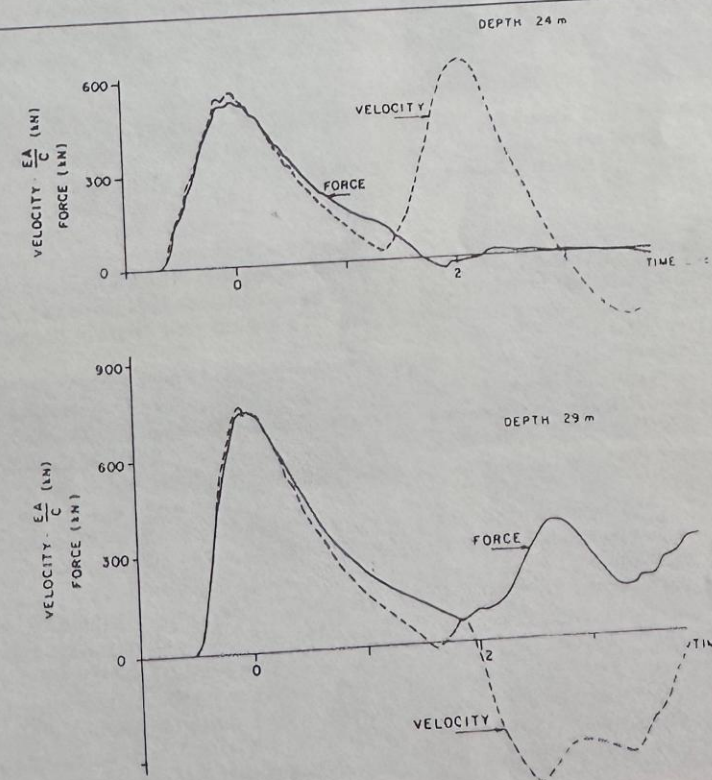

FIGURE 2

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(Continued from P. 3)

force-trace can be calculated. The shape of this calculated force trace depends only on the static and dynamic soil parameters used as input in the analysis and it only remotely resembles the measured force trace. However, by adjusting the input data, the resemblance - the match - can be improved. Ultimately, after 5 to 10 computer runs, the computer trace is made to agree well with the measured trace. The condition for the match is that the soil data - quake, damping, and ultimate shaft and toe resistance values - are those of the soil in which the pile has been driven. In other words, the CAPWAP match has calibrated the wave equation analysis. Thereafter, also with changes of pile lengths, hammer, and pile size even, the wave equation can be used with much greater confidence and the resulting band width be narrowed considerably.

In the CAPWAP process, the static capacity of the pile has been determined. It is rarely identical to the statically tested ultimate capacity of a pile. Consider that the ultimate capacity of a test pile as evaluated from a load-deformation curve can vary by 20% with the definition of failure load applied. Also, only very few tests can produce load values within an accuracy of 5%. Usually, the inaccuracy is about 15% and more. A CAPWAP analysis performed on good measurements taken when a pile penetrates at about 5 to 8 blow/pile will provide values of ultimate capacity which are reliable and representative for the static behaviour of the pile at the time of the driving. Provided the static test is equally well performed (not always the case) the two values of static capacity are within a 15% to 20% deviation, which for all practical engineering purposes can be taken as complete agreement. Building codes in Europe and in Canada recognize this and have accepted the dynamic methods as equal to routine static pile testing. As the costs of one conventional static test equals ten to twenty and more dynamic tests and analyses, the savings can be considerable.

The dynamic monitoring does not replace static testing and conventional inspection methods, it compliments them. Commonly, instead of, say, three static tests, only one is performed and combined with dynamic monitoring and analysis. Thus, gaining money and time along with an improved confidence.

Dynamic monitoring has got the reputation of a "black-box technique" and a "cure-all." Consequently, there are many sceptics and many critical voices. However, the knowledgeable and experienced piling man is not replaced by the technique. Instead, he has become even more needed, because without him the technique is just a fancy tool best left in the shed. Today, the number of people who understand both the advantages of the dynamic monitoring and the limitations - the latter is not the least important knowledge - are few. However, the numbers are rapidly increasing and it is a fairly safe prediction that in about five years' time, no major project involving driven piles will be undertaken without dynamic monitoring and analysis.

(Editor's note: Bengt Fellenius' lecture contained a large number of case histories from North American piling projects, which space limitations do not allow to be presented.)

Cleveland: ballots reported

(Continued from P. 1)

Section 1. The Executive Committee shall consist of all the elected officers and the most recent available past President.

Section 3. The Executive Committee shall meet at the call of the President or on request of any two members of the Executive Committee to the Secretary, and the Secretary shall call a meeting within ten days after such request on five days written notice to the members of the Executive Committee.

ARTICLE XII - NOMINATING COMMITTEE AND ELECTION OF TRUSTEES

Section 1. There shall be a Nominating Committee of at least three members in good standing, appointed by the President not less than six months preceding each Annual Meeting.

Section 2. The Nominating Committee shall appoint a slate of candidates for election to the Board of Trustees not later than four months prior to the next Annual Meeting. The number of candidates so nominated shall be equal to the number of Trustees whose terms will expire at such Annual Meeting plus any vacancy which also exists at such Meeting. No member of the Nominating Committee shall be eligible for nomination to this slate of candidates.

Section 3. The Nominating Committee shall insure that all candidates will stand for election and, if elected, will serve as a Trustee. The Secretary shall report the slate of candidates in the Newsletter to be issued between 90 days and 4 months before the Annual Meeting or in a special mailing to DFI membership.

Section 4. Members in good standing of the Institute may be added as candidates to the slate developed by the Nominating Committee by filing a notice of nomination with the Secretary not less than seventy-five calendar days before the next following Annual Meeting. Such notice of nomination must be signed either by at least 50 members in good standing or 10 percent of the membership of the Institute in good standing if that be less. The Secretary shall include the names of all candidates so nominated in the Ballot for Election of Trustees. Additional spaces shall be provided for write-in names.

Section 5. The Secretary shall send a mail ballot for Election of Trustees to each member at his or her latest mailing address not less than sixty calendar days prior to the next following Annual Meeting, with instructions included to return all ballots at least twenty calendar days prior to the Annual Meeting. The ballot announcing the nominees shall be limited to the name and pertinent qualifications of each nominee for office. A double envelope shall be included, so arranged that each voter may be identified but his ballot kept secret. All ballots returned at least twenty calendar days prior to the Annual Meeting shall be counted by a Committee of Tellers appointed by the President. Each nominee and the Board of Trustees shall be promptly notified of the results by the Secretary.

Conference set for May 1984

ST. LOUIS, MO -- Final programs are now available for the International Conference on Case Histories in Geotechnical Engineering set to take place here from May 6 through 11, 1984, it was announced recently by Conference Chairman Shamsher Prakash.

For more information contact Prakash, University of Missouri-Rolla, Rolla, Missouri 65401 (USA); (314) 341-4461.