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PERFORMANCE OF PILE DRIVING HAMMERS

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INTRODUCTION

The understanding of pile driving and pile driving hammers is difficult; first because of the interaction of many components such as ram, impact block, cushion assembly, pile and soil, and second because of the very short duration of the total impact phenomenon. The potential success of theoretical investigations is limited by the large number of unknowns, primarily regarding material behavior and component interaction. Experience and engineering intuition have, therefore, been most important to hammer designers and users. However, problems such as pile overdriving or damage frequently occur and unnecessary blow count requirements lead to losses of time and money.

With the recent developments in electronic measurement techniques it has become possible to obtain, experimentally, a better insight into the hammer action. However, the interpretation of the measured data is often difficult. It is the purpose herein to show, by means of simple theoretical models, how force and acceleration measurements can be used for a meaningful evaluation of quantities such as energy transfer and forces in pile and hammer components.

Most of the data used was collected in an effort to predict pile bearing capacity (2,3). Hammer performance studies were not conducted on a systematic basis. Thus, the data only reflect a more or less accidental encounter of hammer types in the State of Ohio.

THEORETICAL BACKGROUND

Traveling Wave Solution.—The behavior of a hammer striking a pile can only be understood when the interaction of both the hammer and the pile is studied. Furthermore, the pile motion is greatly dependent upon the soil

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properties, adding additional complication to the analysis. Simplifying assumptions have to be made to obtain a general understanding of the various parameters involved. Thus, a pile, either fixed or free at one end and struck by a mass, will first be considered as it was presented by St. Venant (4). Using the general solution of the one-dimensional wave equation he developed the concept of solving for stresses from and ram velocities by superimposing properly chosen traveling stress waves. Such waves travel with a speed, c, which can be computed from

$$c = \sqrt{\frac{E}{\rho}} \quad \text{. . . . . (1)}$$

in which E = Young's modulus and ρ = the mass density of the pile material. Thus, if the pile has a length, L, an impact wave will reach the pile bottom after a time, L/c, and its reflection at the bottom end arrives at the pile top a time, $2L/c$, after impact. Wave reflections arise due to discontinuities along the pile such as a change in cross section, the most extreme case being the pile end. Resistance forces also create stress waves in a pile that can be superimposed on the impact wave (3).

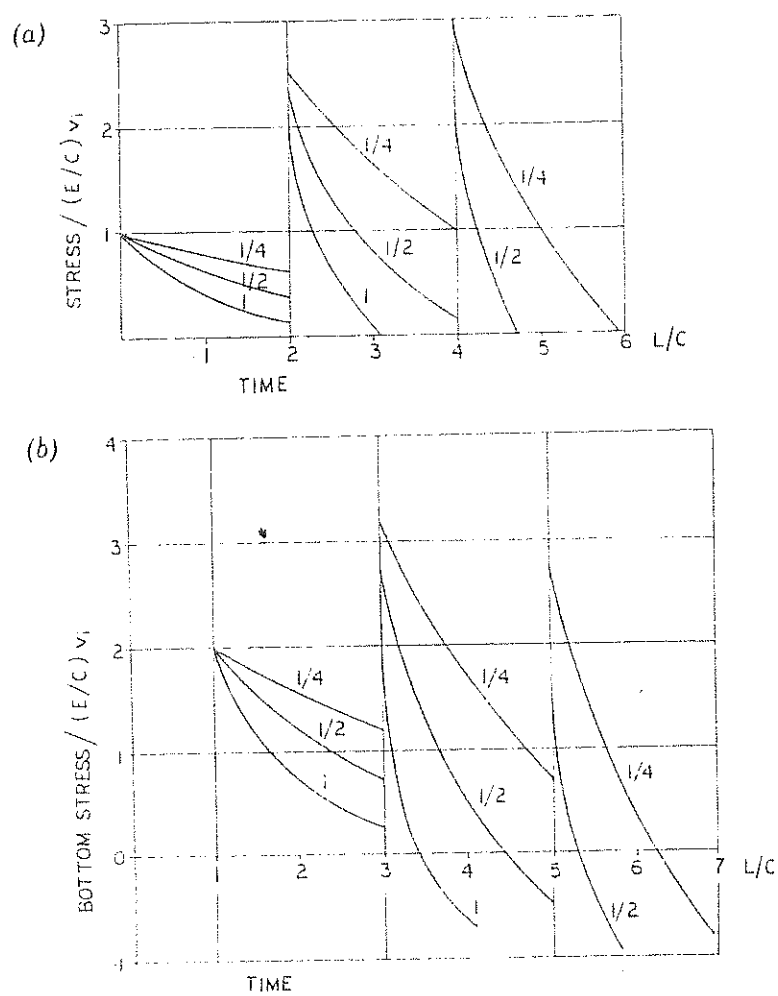


FIG. 1.—ST. VENANT SOLUTION FOR FIXED-END PILE AND VARIOUS PILE TO HAMMER WEIGHT RATIOS: (a) STRESS AT PILE TOP; (b) STRESS AT PILE BOTTOM

Using the approach of traveling stress waves, St. Venant computed pile top stresses by assuming a perfectly elastic impact of a rigid mass with an elastic rod. Results for a fixed-end pile are given in Fig. 1(a) where curves for three different pile-to-hammer mass ratios α are plotted. The stresses are nondimensionalized by division by the factor $v_i E/c$, v_i being the velocity of the ram at the instant of impact. Important observations are, first, the fact that the pile top stress at the time of impact depends only on the ram impact velocity, v_i. Second, the pile top stresses decay (logarithmically) at a higher rate for larger pile-to-hammer mass ratios. Thus, zero stress which is equivalent to hammer-pile separation, occurs later for larger hammers. It is also important to note that the maximum pile top stress occurs with the arrival of the reflected waves at a time $2L/c$ for α equal to one and two and at a time $4L/c$ for α equal to four.

The curves in Fig. 1(a) can also be used to consider the free end pile struck by a mass. Obviously, such a pile will move without bound, but, before the time, $2L/c$, the pile top will experience the same stresses as in the fixed end case, because no reflection wave has yet arrived at the top. At $2L/c$ a tension wave arrives and pulls the pile away from the ram. Thus, in the case of a free end pile at time $2L/c$ the ram separates from the pile for all pile-to-hammer mass ratios.

In order to obtain an estimate of the maximum resistance force that can be overcome by a certain hammer-pile system, the pile bottom stresses were plotted in Fig. 1(b) for the fixed pile. In general, these stresses are somewhat larger than the top stresses. Maxima occur at the bottom at time L/c after the corresponding top maximum. However, it is important to note that the first nonzero value, at time L/c, is twice the pile top stress at impact. In most practical cases maximum bottom stresses occur at this time since further stress peaks are reduced by stress reflections at intermediate points along the pile and energy losses to the soil. Only in cases of small pile-to-hammer mass ratios (less than 1/3) with very small skin resistance and high toe resistance (bedrock) is it possible that the pile obtains higher stress peaks at a later time. For the more usual case, however, the maximum force that can be reached at the pile bottom is $2.0\ v_i EA/c$ in which A is the pile cross-sectional area. The important quantities for driving a pile of given material to a certain resistance in a specific soil are, therefore, hammer impact velocity and pile cross-sectional area.

In Fig. 2(a) the pile top velocities, divided by v_i, corresponding to the stress curves in Fig. 1(a) are shown. These velocities are also those of the ram because pile and hammer are in contact as long as no separation occurs. Of course, as in the case of stresses, the velocities are valid for the free pile until item $2L/c$, when separation occurs. Comparing stress, Fig. 1(a), with velocity, Fig. 2(a), curves for the pile top it can be seen that pile top velocity v_i is proportional to pile top stresses σ_p before time $2L/c$. In general this proportionality holds as long as no upwards traveling waves (due to resistance or changes in pile cross section) reach the pile top. Thus, for this time interval after impact

$$v_p = \sigma_p \frac{c}{E} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad (2)$$

This relation can be used to check measurements of stress and velocity as Eq. 2 holds at least until the first peak value of velocity occurs (providing that the rise time of the force during impact is short). The preceding also shows that peak force values at impact bear no relationship to pile resistance.

Because energy considerations are commonly used for pile capacity computations an analysis of energy transfer is appropriate. At the instant of impact the ram contains kinetic energy:

$$E_k = \frac{1}{2}\, M_r (v_i)^2 \qquad (3)$$

in which M_r = the mass of the ram. The energy transferred to pile E_t can be computed at any time t from

$$E_t\,(t) = A \int_0^t \sigma_p(t)\; v_p(t)\; dt \qquad (4)$$

Its maximum value was called ENTHRU in Ref. 1. Using the curves of Figs. 1(a) and 2(a), $E_t\,(t)$ was computed and plotted in Fig. 2(b) after division by

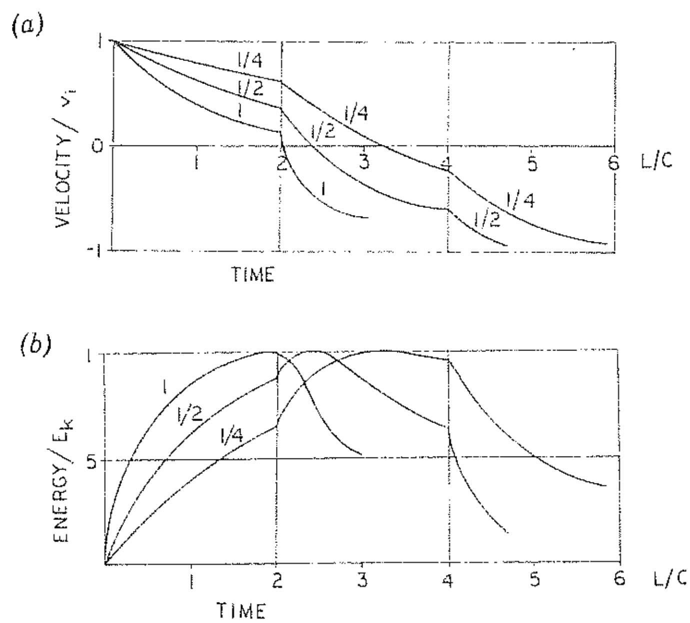
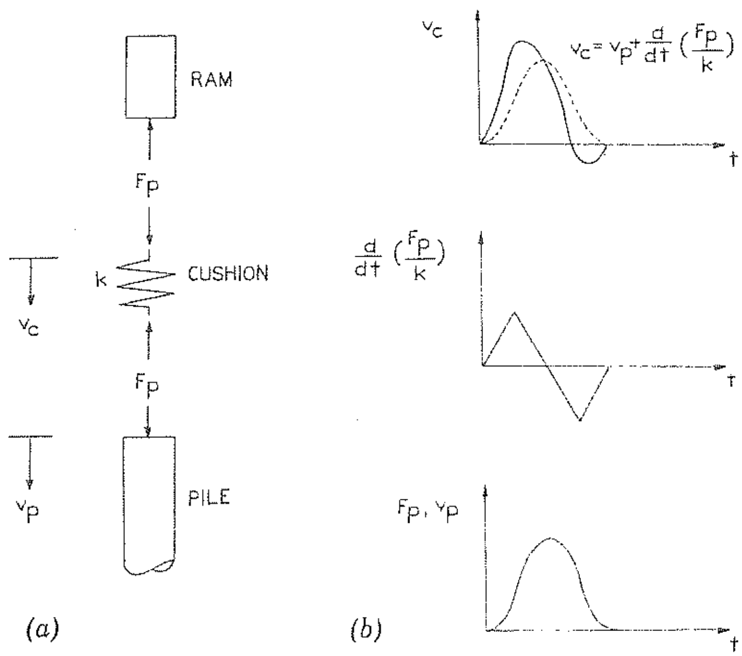


FIG. 2.—ST. VENANT SOLUTION FOR FIXED-END PILE AND VARIOUS PILE TO HAMMER WEIGHT RATIOS: (a) PILE TOP VELOCITY; (b) TRANSFERRED ENERGY

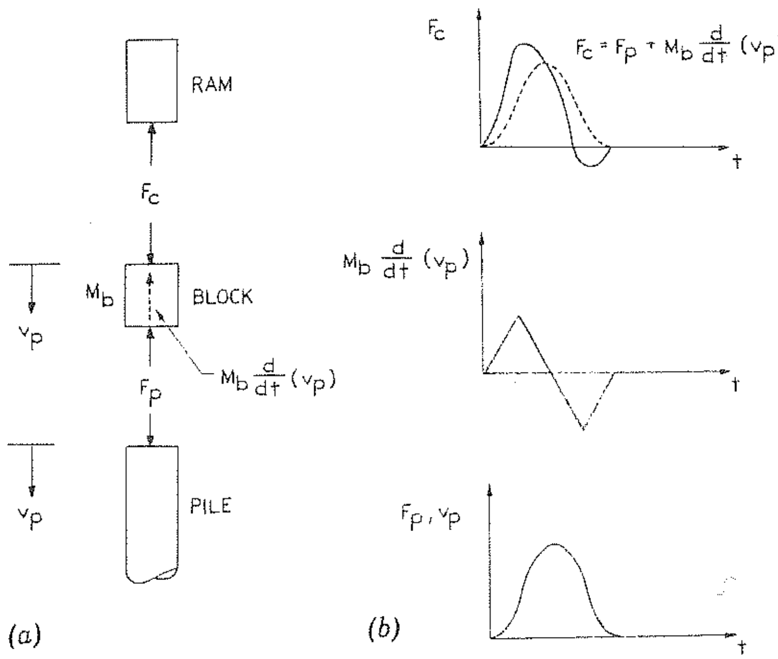
E_k. For the free pile case these curves apply until time $2L/c$ after which their value is constant, $\sigma_p(t) = 0$. For the fixed end case all curves reach a value of one (the total hammer energy is transferred to the pile) at the time of zero velocity after which the pile rebounds and returns energy to the hammer until separation occurs. Again, after separation the energy value stays constant. This constant value is the total energy transferred which, for this idealized case, produces pile vibrations only in the fixed end case and a net motion plus oscillations in the free pile case. In reality some of the available energy would also do work on the soil. In theory, with $\alpha = 1$ for a free pile, up to 99 % of the energy is permanently transferred, for a fixed pile the value is more than 50 % of the energy, Fig. 2(b), although none is used to overcome resistance forces. That portion of the energy that is not transferred to the pile stays in the hammer (free pile) or is returned to the hammer (fixed pile).

Hammer Components.—Thus far the only case treated was where the hammer consists of a single rigid mass which strikes the pile in a perfectly elastic



(*a*) (*b*)

FIG. 3.—EFFECT OF CUSHION IN DRIVING SYSTEM: (*a*) MODEL; (*b*) VELOCITY ON TOP OF CUSHION, DIFFERENCE VELOCITY BETWEEN TOP AND BOTTOM OF CUSHION, AND VELOCITY AT BOTTOM OF CUSHION



(*a*) (*b*)

FIG. 4.—EFFECT OF BLOCK IN DRIVING SYSTEM: (*a*) MODEL; (*b*) FORCE ON TOP OF BLOCK, DIFFERENCE FORCE BETWEEN TOP AND BOTTOM OF BLOCK, AND FORCE AT BOTTOM OF BLOCK

manner. While the assumption of a rigid ram is usually justified it is not possible to disregard the presence of hammer components that can be categorized as cushions and blocks. Cushions are flexible and light while blocks are rigid and heavy.

Consider Fig. 3(a) where the system of a ram striking a cushion and pile is shown. Due to the flexibility of the cushion the pile velocity, v_p, is different from the velocity of the top of the cushion, v_c. However, the force on top of the cushion is equal to that in the pile, F_p, because no inertia effects are present. Assuming the cushion to behave like a linear spring of stiffness k, the spring compression is F_p/k and the relative velocity between the top and bottom face of the cushion is $(d/dt)(F_p/k)$. The total velocity at the cushion top (or that of the ram) is the sum of the pile velocity and the velocity due to cushion compression.

These relations are represented in Fig. 3(b) where it is assumed, for illustration purposes, that pile forces and velocity are proportional and piecewise parabolic (bottom graph). The relative cushion top to bottom velocity is, therefore, piecewise linear (middle graph). The ram velocity, v_c, is shown in the top graph. If now the velocity of the pile is compared with the velocity of the ram, the effect of the cushion is shown. The peak velocity in the pile is less than that of the ram showing that the peak pile force is reduced by the cushion. Also, the duration of the positive velocity is increased in the pile.

The case of a rigid block of mass M_b can be treated in a similar manner. Fig. 4(a) shows the system of forces and velocities. Because of the block rigidity no change in velocity occurs between the top and bottom surfaces but the force at the top of the block will be different by an amount equal to inertia force $M_b\, dv_p/dt$. As a consequence, a block spreads a force spike over time by reducing its peak value. This effect is demonstrated in Fig. 4(b).

All hammer components store energy during a hammer blow. A block contains kinetic energy while it moves, a cushion stores strain energy while being compressed. This energy is not necessarily lost but is returned to the system during a later phase of the hammer blow.

Energy Losses During Impact.—Probably the most important cause for losing hammer energy is material plastification which occurs at interfaces of hammer components, at the pile top and in cushion materials. Depending on the way the hammer acts it is possible that some components impact and separate or at least load and unload several times during a single impact. In this way the cushion goes through more than one loading cycle and nonelastic impact of hammer components gives rise to higher energy losses than could be explained otherwise.

In computing the energy reductions due to the interaction of hammer components and the pile a coefficient of restitution, e, is commonly used (e.g., Modified Engineering News Formula, Hiley Formula). Denoting the mass of hammer components below the ram, including that of the pile, as M_c the reduced energy is

$$E_n = E_k \frac{M_r + e^2 M_c}{M_r + M_c} \quad \text{(5)}$$

The coefficient of restitution is one for fully elastic impact which leads to $E_n = E_k$. When fully plastic impact occurs e is zero and the energy is reduced by the factor $M_r/(M_r + M_c)$. If e is between zero and one the impact is called elastoplastic. Theoretically in both the elastic and the elastoplastic case the ram separates immediately from the assembly of the other hammer components which then transfer part of the energy to the pile while the ram still contains another part of it. Only in the case of plastic collision does the ram and all hammer components together transfer the hammer energy to the pile.

This theory was derived by assuming a collision between two rigid bodies (ram and other hammer components plus pile). Of course, the presence of a flexible cushion block and a very flexible pile and the fact that more than one rigid mass are among the hammer components (such as anvil and cap) make the basic assumptions of the theory questionable. With results from measurements the analysis of this point will be continued in the following section.

RESULTS FROM MEASUREMENTS

Measuring Systems and Analysis of Michigan Data.—During recent years more and more measurements have been made on hammers and piles during driving. For the analysis herein, results from the Michigan study (1) and those from the Case Western Reserve University project (2,3) will be used. In both cases, force and acceleration were measured as a function of time.

Fig. 5(*a*) shows the location of force and acceleration transducers as described in the Michigan Report. The force transducer having a weight of approximately 500 lb (2.3 kN) was bolted to a cap, that in the case of pipe piles, rested on top of a pile adaptor. One accelerometer was bolted to the bottom flange of the force transducer. In this way the transducer was placed below the cushion assembly but above the pile top, thus becoming an additional hammer component. Fig. 5(*b*) shows the measuring system used in the Case Western Reserve work. A transducer made from standard pipe with a wall thickness not much more than the pile wall was bolted to a 1-in. plate that was welded to the pile top. In this study strain gages were also attached directly to the pile wall to ensure that the transducer output represented the forces in the pile. Two accelerometers were attached to the pile wall at 180° to cancel out gross bending effects.

A record that was taken under comparable circumstances is selected from each study. Fig. 6(*a*) shows the plot of velocity (multiplied by the proportionality constant, EA/c) and force obtained on LTP-5 at the Belleville site in Michigan. The pile, having a length of 66 ft (20 m), was of 12-in. (30-cm) pipe with a 0.179-in. (4.6-mm) wall thickness. The hammer was a Delmag D-12. The curves of force and velocity (obtained by integration of the acceleration), shown in Fig. 6(*a*) were taken using the same hammer and pile type. Only the pile length and soil conditions were different. The record was taken in Logan, Ohio by the Case Western Reserve Study.

The two velocities of Fig. 6(*a*) and 6(*b*) show a very similar behavior while the forces differ quite substantially. The impact spike of the Michigan record reaches more than 700 kips (3,110 kN) which, if present in the pile, would mean a stress of more than 100 ksi (69 kN/cm^2). This fact and the lack of proportionality between force and velocity in the initial portion of the record, which holds in Fig. 6(*b*) suggest that the forces of the Michigan study do not represent forces in the pile. In fact, a block (Universal Cap) was inserted between transducer and pile top, Fig. 5(*a*). Using the considerations of the preceding section an example calculation was performed for LTP 6 at the Muskegon site. Fig. 7(*a*) shows how the force record, by use of the acceleration record and the mass of the block, [1,400 lb (6.2 kN) for Universal cap + 500 lb (2.3 kN) for pipe protector gives 1,900 lb (8.5 kN)] is modified and the initial peak reduced. The high peak at impact completely disappears. A rather spiky looking curve

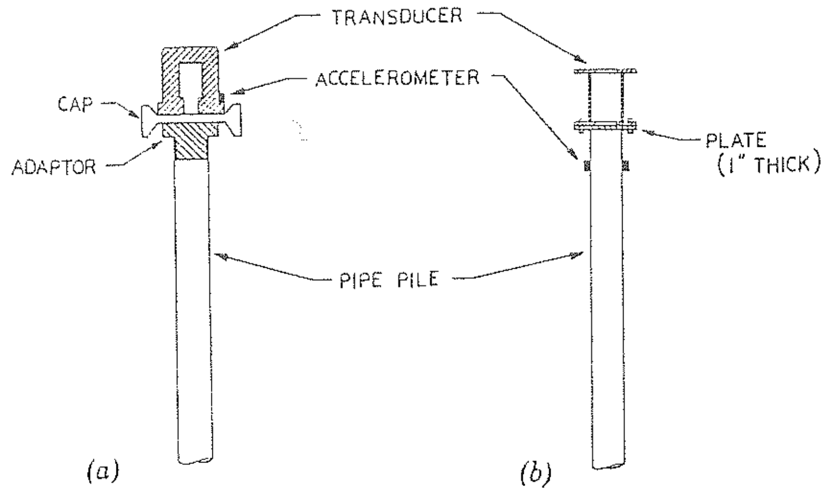


FIG. 5.—MEASURING SYSTEM: (*a*) MICHIGAN STUDY; (*b*) CASE WESTERN RESERVE STUDY (1 in. = 2.54 cm)

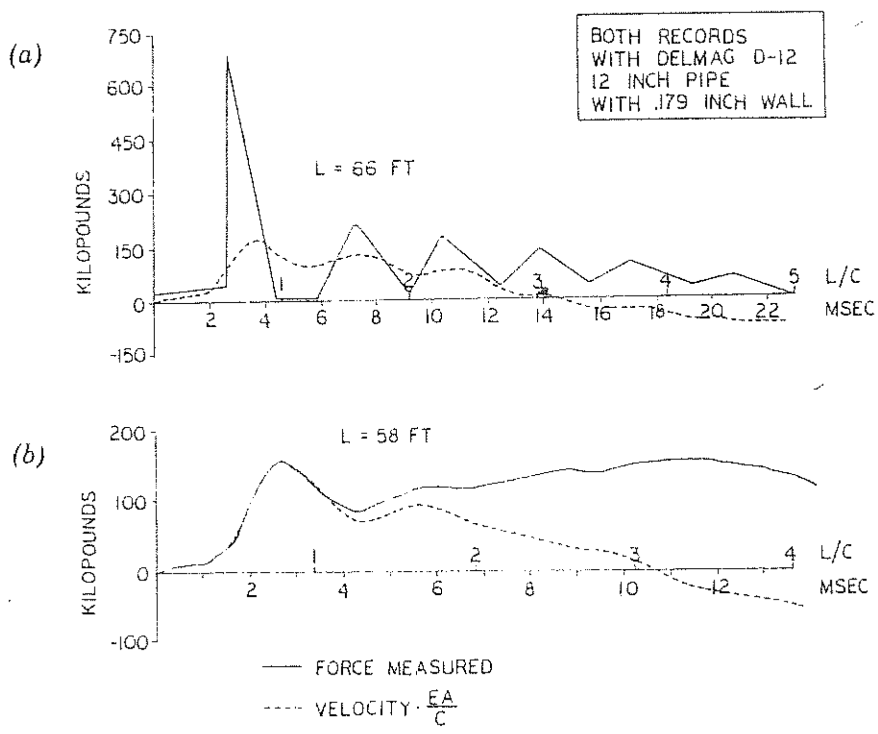


FIG. 6.—RECORDS TAKEN UNDER SIMILAR CONDITIONS: (*a*) BELLEVILLE SITE (LTP 5), REF. 1; (*b*) LOGAN SITE, REF. 2 (1 kip = 4.45 kN; 1 ft = 0.305 m; 1 in. = 2.54 cm)

results. That could be expected as it reflects the appearance of the acceleration record and the manner in which both records were converted to digital form. Thus, a smoothing process, by time averaging, seems to be reasonable and justified. Fig. 7(b) shows the computed together with the smoothed pile force curve. In Fig. 7(c) the smoothed curve is compared with the velocity obtained by integrating the measured acceleration. There is a clear indication of proportionality at the time of impact between pile force and pile velocity. Note that some other records of Ref. 1 did not give as good results as the one demonstrated above. However, it appears that the published force records were approximated with straight lines less carefully than necessary for calculations involving the even rougher acceleration curve. Also, rotation of the transducer could have affected the acceleration measurements.

Comparison of Force and Velocity Records with St. Venant's Solution.—The traveling wave solutions presented in a preceding section are valid only for the case of a rigid mass striking a pile directly and elastically. Both pile-to-

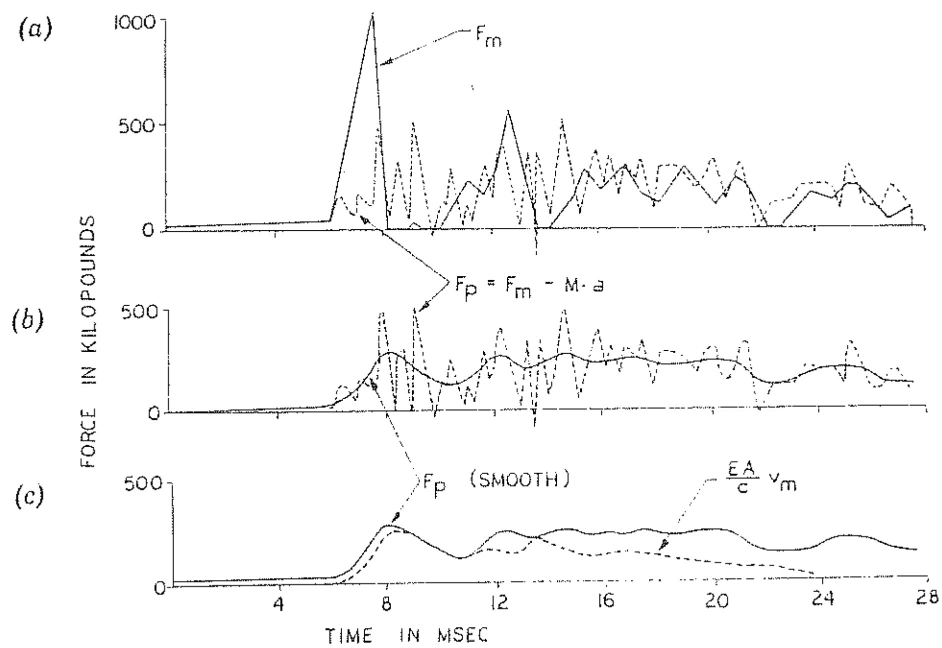


FIG. 7.—REDUCTION OF MICHIGAN FORCE RECORD (Muskegon LTP 6) TO FORCES AT PILE TOP USING MEASURED ACCELERATION: (a) MEASURED FORCE F_m, AND PILE TOP FORCE, F_p; (b) PILE TOP FORCES BEFORE AND AFTER SMOOTHING; (c) COMPARISON OF SMOOTHED PILE TOP FORCES WITH VELOCITY FROM MEASURED ACCELERATION (1 kip = 4.45 kN; 1 ft = 0.305 m; 1 in. = 2.54 cm)

hammer weight ratios and impact velocity were found to be important quantities. It is, therefore, useful to study field records of force and velocity at the pile top. Only the Case Western Reserve University results are used in this evaluation because the Michigan records give forces on top of a mass rather than on top of the pile.

Pile driving rams have to first accelerate other hammer components having a large mass in order to move the pile head. It is, therefore, difficult to compare pile-to-hammer mass ratios, of different hammer types. As a guide, ratios will be used defined by α = Pile weight W_p/Weight of Ram, Anvil and Cap W_h. Consider Fig. 8(a) where both pile top force and velocity are plotted as obtained on a steel pipe pile of 50 ft (15.3 m) length, 12 in. (0.31 m) diam and 1/4 in. wall (W_p = 1.68 kips = 7.5 kN). The Diesel hammer, Delmag D-12, had a ram + anvil + cap weight of 4.60 kips (20.4 kN) such that α = 0.37.

The pile encountered relatively small soil resistance forces. The pile top force and velocity show only slightly different behavior except at time $2L/c$ after impact, when the force decreases and the velocity increases (the tension effect arriving from the pile bottom pulls the pile head downward). After that, in contrast to the theoretical solution for a free pile, the pile top force increases again. Thus, due to the presence of soil resistance forces, the still downward moving cap imposes compression forces again onto the pile head. The fuel combustion also adds to the downward motion of the anvil and cap assembly.

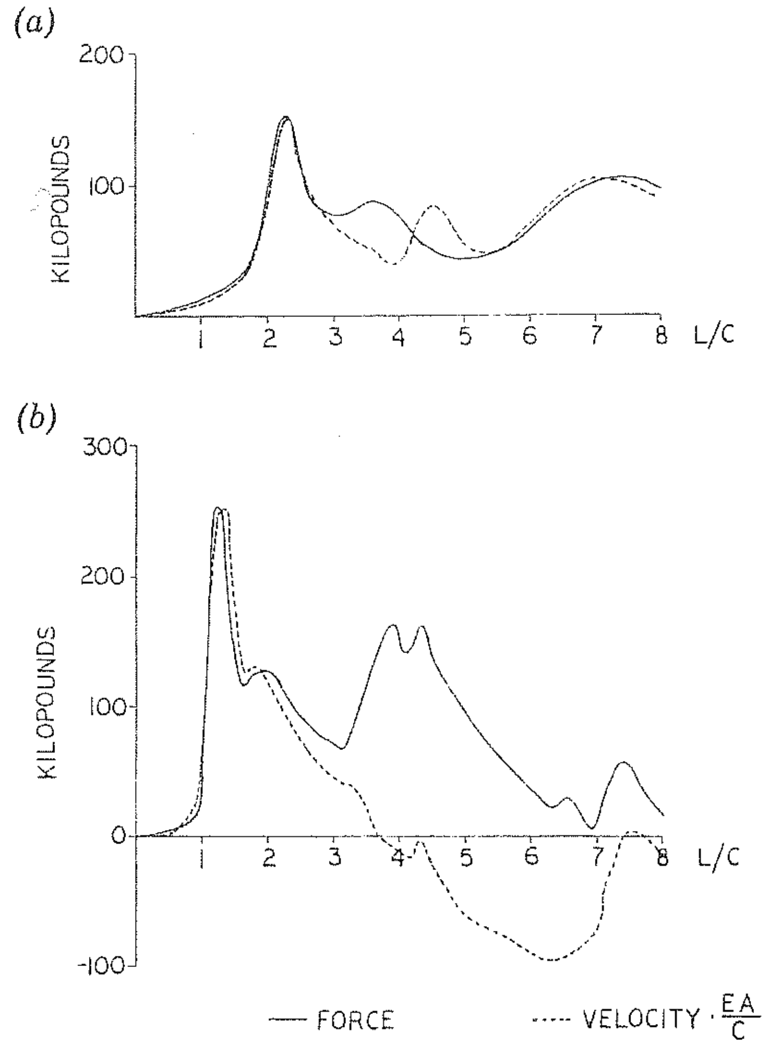


FIG. 8.—FORCES AND VELOCITY (Proportional) MEASURED AT PILE TOP: (*a*) D-12 LOW RESISTANCE; (*b*) D-12 HIGH TOE RESISTANCE (1 kip = 4.45 kN)

Fig. 8(*b*) was taken after the same pile was extended by a 10-ft section and driven to a stiff layer under the same hammer (α = 0.44). Skin resistance was present but of small magnitude and gave rise to small differences between proportional velocity and force before time $2L/c$ after impact. At this time the pile force starts to increase while the velocity continues to decrease. This is a behavior similar to the one of a fixed end pile. The smoother force behavior is due to the limited soil stiffness and the cushion. The maximum force occurs in this record at impact. The corresponding impact velocity, 15 ft/sec (4.6 m/s), is unusually high and decays rapidly. The reason for this high velocity is the large hammer stroke. A large portion of the energy is returned to the hammer, as indicated by the large negative velocity in the later part of the record, while the force is positive. Thus, both pile strain energy and combustion energy are used to drive the ram upward. It is interesting to compare this record with the force obtained from the St. Venant analysis. The rise time at impact is, of course, not instantaneous but requires about 1/4 L/c. For this value of α of 0.44 a second peak stress at $2L/c$ of over twice the first peak is

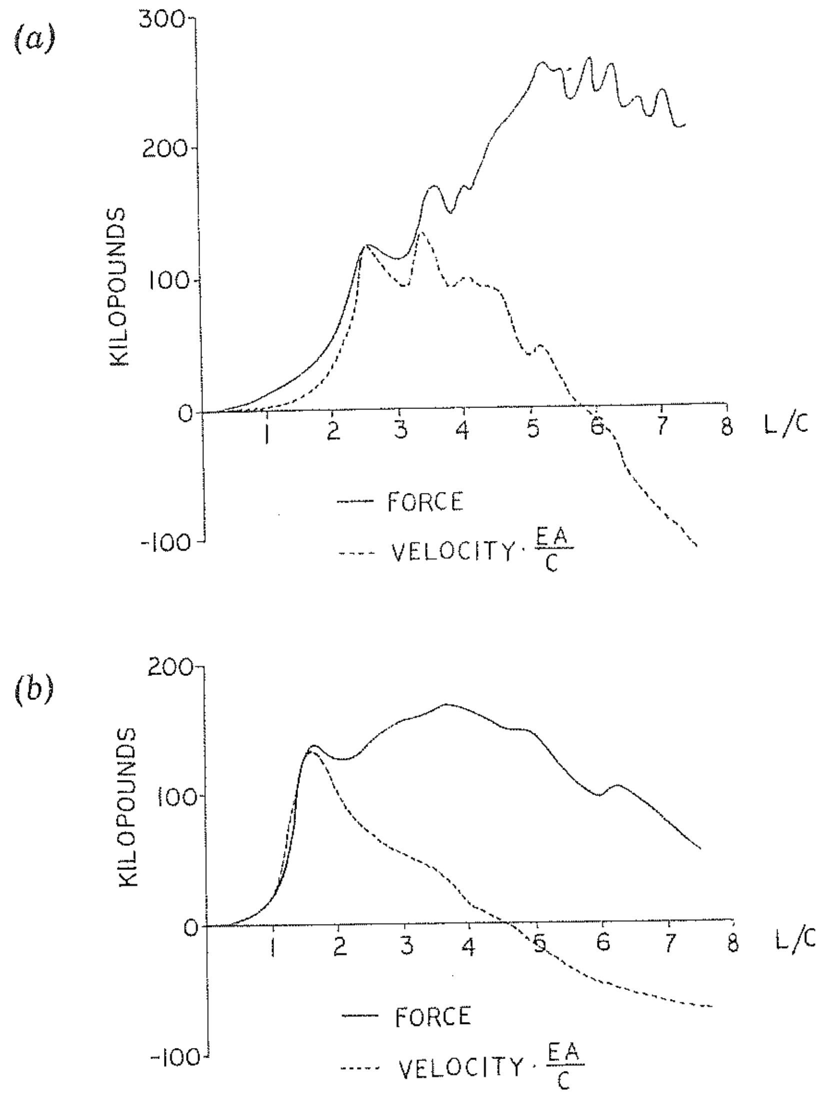


FIG. 9.—FORCES AND VELOCITY MEASURED AT PILE TOP: (*a*) LB 520 HAMMER, HIGH BOTTOM RESISTANCE (Courtesy of the A. Bentley and Sons Company); (*b*) V-50C HAMMER FRICTION PILE (1 kip = 1 kN)

predicted by Fig. 1. The reduction of the peak is probably due to the side resistance present even in this soft soil, the failure of the tip resistance to reach complete rigidity, and the fact that at impact the force rise is not instantaneous.

Fig. 9(*a*) shows the record of a case where a Linkbelt 520 (W_h = 7.63 kips = 34.0 kN) was used to drive a pile 46 ft (14.1 m) long with a cross-sectional area of 6.7 in² (43.2 cm²) thus W_p equals 1.57 kips (7.13 kN) yielding an α of 0.21. The pile bottom support was again very stiff and only small skin resistance forces were present. Although the force curve is much smoother than in the theoretical case the wave return after $2L/c$ after impact can again be observed. This time the pile top force increases to about twice the impact force. Note, that this increase is not due to the hammer combustion which has an effect spread over most of the record.

It should be added here that in Figs. 8(a), 8(b), and 9(a) hammer precompression effects, present before the hammer impacted were subtracted from the force record. These forces are of a static nature and, if not subtracted, make the proportionality check difficult. Further analysis of these effects will be given in the following paragraphs.

Fig. 9(b) shows a record that was taken on a 12-in. (0.31-m) pile with 0.179-in. (4.6-mm) wall and 56-ft (17.1 m) length driven by a Vulcan 50C hammer into sandy and silty soil. It is important to note here that the duration of the hammer blow is comparable to the Diesel hammer record. Thus, fuel combustion alone is not responsible for the length of the record (or stress wave as it is often referred to). Of course, it was not necessary in this case to subtract a precompression force from the record.

TABLE 1.—VELOCITY REDUCTION FOR VARIOUS HAMMERS DUE TO PLASTIC COLLISION 1 kip-ft = 1.36 kN-m; 1 kip = 4.45 kN; 1 fps = 0.305 m/s

Hammer (1)	Manufacturer's rated energy, E_m, in kip-feet (2)	Weight of ram, W_r, in kips (3)	Weight of cap + anvil, W_a, in kips (4)	$W_r/(W_r + W_a)$ (5)	Ram velocity, v_i, in feet per second (6)[a]	Ram velocity after plastic collision, v_i^*, in feet per second (7)[b]	Velocity reduction from plastic collision, in feet per second (8)
DE-30	16.8	2.80	2.17	0.56	19.6	11.0	8.6
D-12	22.5	2.75	1.85	0.60	22.9	13.7	9.2
D-22	39.7	4.85	2.61	0.65	22.9	14.9	8.0
LB-312	15.0	3.86	2.57	0.60	15.8	9.5	6.3
LB-520	26.3	5.07	2.56	0.67	18.3	12.2	6.1
V No. 1	15.0	5.0	1.00	0.83	13.9	11.5	2.4
V-80C	24.5	8.0	2.14	0.79	14.0	11.1	3.9

[a] $v_i = \sqrt{(2E_m/W_r)\ 32.2}$.
[b] $v_i^* = [W_r/(W_r + W_a)]\ v_i$.

In the four examples of Figs. 8 and 9 impact velocities as measured were between 7 fps and 15 fps (between 2.1 m/s and 4.6 m/s). Note that these values were extreme for very weak and stiff soil resistance. Usually measured values in Refs. 1 and 2 are between 8 fps and 12 fps (between 2.4 m/s and 3.7 m/s). However, the theoretical value computed from rated hammer energies when using Eq. 3 and solving for v_i are much higher as demonstrated in Table 1. The rated energy values listed in this table are taken from Ref. 3.

Several effects are responsible for the reduction of impact velocity in the driving system. The cushion reduces the velocity spike, energy is lost during the collision of hammer components and pile and, in the case of Diesel hammers, velocity is lost during the compression period before impact.

Cushion Effects.—As covered in a preceding section a cushion reduces a velocity spike by an amount equal to the derivative of the force in the cushion divided by the cushion stiffness. As an example consider the Belleville LTP 5 record in Fig. 6. The cushion of the D-12 hammer consisted of a 15-in. by

15-in. by 5-in. thick (38-cm × 38-cm × 13-cm) oak block. Assuming a modulus of elasticity of 2×10^6 psi (1,380 kN/cm²) for this material the cushion stiffness if $k = 1.08 \times 10^6$ kips/ft (1.58×10^6 kN/cm). The very sharp rise time of the force record produces a $\Delta F/\Delta t = 3.3 \times 10^6$ kips/sec (14.7×10^6 kN/s). Thus, $v = (\Delta F/\Delta t)(1/k) = 3.1$ fps (0.93 m/s) where the inertia effect of the cushion helmet (between transducer and cushion) was neglected. Of course, this velocity reduction value is only an average as the force versus time relation was assumed to be linear.

The record of Fig. 7 shows a lower rise and indicates, therefore, a smaller velocity reduction.

Velocity Reduction Due to Inelastic Ram Collision.—The maximum velocity value at impact, occurs within such a very short time interval after impact that neither pile mass nor soil resistance affects its value. However, anvil and cap mass have an influence because they transfer the ram momentum to the pile. To give a bound to the maximum possible reduction, velocities were

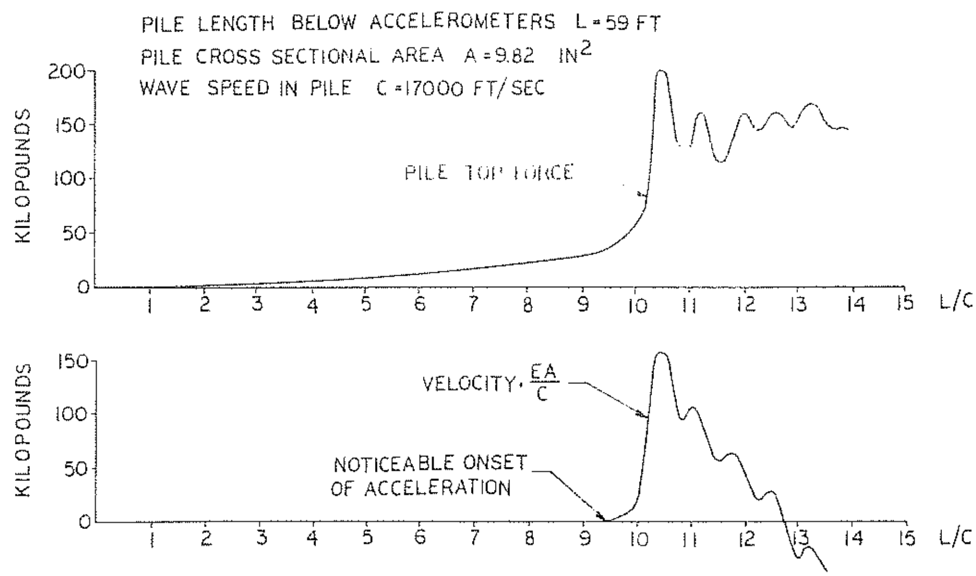


FIG. 10.—TYPICAL FORCES AND VELOCITY RECORD TAKEN UNDER DIESEL HAMMER BLOW (1 kip = 4.45 kN; 1 in. = 2.54 cm; 1 ft = 0.305 m)

calculated assuming a plastic collison ($e = 0$). The results, which are listed in Table 1, indicate pile impact velocities close to the measured ones. The model used in this example computation is, of course, of only limited value. It implies that for elastic or elastoplastic impact higher velocities of the anvil plus cap are possible as their mass is smaller than that of the ram and separation can occur immediately.

Velocity Reductions Due to Compression in Diesel Hammers.—All records taken on piles driven by Diesel hammers show a slowly increasing force for a relatively long time before impact due to gas compression in the combustion chamber of the hammer. Fig. 10 shows a record with a compressed time scale. Of course, this slowly increasing force, although not of large magnitude, resists the ram motion, while it leads to only small pile velocities. From elementary dynamics this reduction can be calculated by integrating the force over time. In the case of Fig. 10 which is a record of a blow under a Link Belt 440 hammer this computation leads to a velocity reduction of 2.7 fps

(0.82 m/s). Other Diesel hammer types produce different compression forces. Steam or air hammers do not have this effect.

The analysis of velocity reduction explains the differences between the theoretical and the measured pile behavior. All effects reduce the theoretical spike at impact and spread it over some time.

Observations on Michigan Records.—Considering only the records of force and velocity at the pile top it could be concluded that the hammer impact is a relatively smooth phenomenon. However, the Michigan records show a very spiky force behavior. Consider Fig. 6 where the force record first shows a large spike which is due to the metal-to-metal impact of the ram with the anvil. After this spike the force is zero for some time. This is a clear indication of separation between cushion assembly and transducer. After this time the force oscillates between zero and some decreasing amplitude. These cycles of loading and unloading must be present in the cushion. It is in such a case meaningless to estimate losses using the theory of two colliding rigid bodies as is done in deriving Eq. 5.

Another remark seems appropriate. The force spikes recorded by the Michigan investigators at the time of impact were created by the insertion of the transducer and Universal cap. A larger mass below the transducer would lead to even larger force spikes and could eventually lead to the destruction of the instrument. The magnitude of these spikes, therefore, bears no relationship to the pile force.

Measured Energy.—The Michigan study produced, as an important result, energy values that were computed from the above discussed force and velocity records. These energy values were often regarded with scepticism. Of course, integration of the measured acceleration curve and subsequent integration of force times velocity (see Eq. 4) is not an easy matter. However, the method of correcting the displacement curve developed by the Michigan investigators is probably quite reliable although final displacements do sometimes disagree with the blow count. Another source of error could be the insertion of an extra mass (transducer plus Universal cap) that creates losses at interfaces which are otherwise not present. In general, the energies reported by the Michigan investigators are similar to those determined from the data of Refs. 2 and 3.

A large number of results is compiled in Ref. 1 and no attempt is made herein to add further data. It is, however, intended to review the way energy is transferred to the pile using the rather extreme examples of Figs. 8 and 9. Those curves were used to compute the transferred energy according to Eq. 4 and the results are plotted in Fig. 11. The effect of the compression force was included.

Curve a shows the energy curve for the pile with the small resistance of [illegible] 8(a). The energy is increasing even after time $2L/c$ after which separa[illegible] between pile and hammer takes place in the theoretical case. This indicates that fuel energy is consumed by the pile. It could be argued that this proves that Diesel hammer energy can be computed by adding ram energy (ram weight times stroke) to the fuel energy. Note, however, that the hammer does not continue to run if all fuel energy is transferred to the pile. It then has to be restarted (Indeed, this is an undesirable feature of Diesel hammers in extremely easy driving).

The case of curve b in Fig. 11(a) is similar to the fixed end case in Fig. 2(b) where the energy curve reaches a maximum value at time $2L/c$ after impact. Then the transfer of energy back to the hammer starts. It should be added here that this record was obtained with the lowest hammer throttle setting. Curve c shows a similar behavior in correspondence to Fig. 9(*a*) and curve d also shows the same for the air hammer.

Cases as demonstrated by curves b and c often lead to misunderstanding in construction control since hammer fuel injection has to be reduced. (Air or steam hammers would automatically not accept as much pressure energy.) It is then argued that the Diesel hammer does not deliver sufficient energy. On the contrary, the hammer may offer even more energy to the pile but because of pile and soil elasticity a substantial portion of that energy is returned back to the hammer. In such cases the pile has usually reached a larger static capacity. For steam and air hammers, both single and double acting, ENTHRU is approximately constant at a specific operating pressure regardless of driving resistance. However, the behavior of Diesel hammers is quite

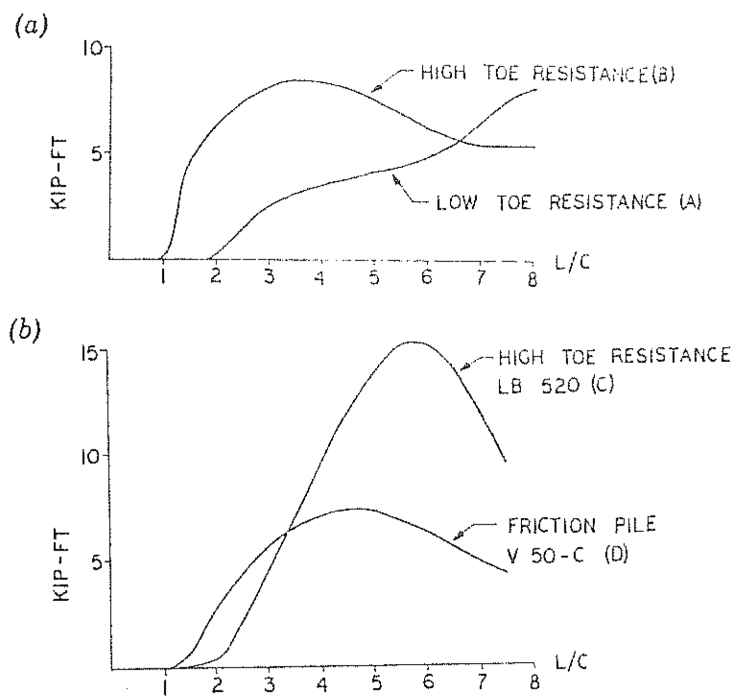


FIG. 11.—ENERGY TRANSFER VERSUS TIME CURVES: (*a*) FOR D-12 DIESEL HAMMER; (*b*) FOR LB-520 DIESEL AND V-50C AIR HAMMER (1 kip-ft = 1.36 kN-m)

different. For very hard driving ENTHRU is closely related to the ram rebound height (or bounce chamber pressure for a closed end hammer) as almost all of the energy transfer to the pile occurs prior to, or in the early stages of, combustion. In soft driving a substantial amount of energy transfer to the pile comes directly from the combustion pressure. Thus, the height of ram fall is reduced and likewise impact velocity and force.

Pile Stresses.—Damage often occurs when a pile is overdriven, i.e., when only very small penetrations are reached and a large number of blows are applied with large returns of hammer energy to the ram. The problem is accentuated when the pile-to-hammer weight ratio is small. An example of such a case is shown in Fig. 9(*a*). For larger pile-to-hammer weight ratios, like in Fig. 8(*b*) pile damage is less likely because the maximum stress occurs at impact. Eq. 2 gives for the impact stress

$$\sigma_i = \frac{E}{c} v_i \quad (6)$$

which in the extreme case of v_i = 15 fps (4.6 m/s) and dynamic steel properties E/c = (31,000/17,000) ksi/fps, i.e., (2,400/5,190) kN/cm²/m/s leads to σ_i = 27.4 ksi (18.9 kN/cm²). The stress at the pile bottom can only reach twice this value in the practically impossible case of a fixed end with no side resistance. Thus, damage due to the impact velocity seems unlikely. However such cases occur and are probably explained by stress increases due to eccentricities in the driving systems and stress concentrations due to uneven contact surfaces, both at the pile top and bottom.

Tension cracks can occur in concrete piling in the case of small soil resistence. For such cases Diesel hammers seem more suitable than steam since they produce small impact velocities in each driving and a continuous pile top force due to fuel combustion.

CONCLUSIONS

Based on the preceding work a number of conclusions are appropriate.

1. The Michigan records were shown to be meaningful and correct within the transducer system used. The energy values computed by the Michigan investigators can, therefore, be considered correct. However, the forces reported are forces within the driving system not in the pile and they depend on the arrangement and configuration of that system. If the intent is to measure forces in the pile then a transducer having approximately the stiffness of the pile should be inserted below all heavy hammer components. If forces are to be measured at interfaces of hammer components then caution should be exercised in the transducer design because the peak forces may be much larger than the pile forces.

2. The driving ability of a hammer depends on the impact velocity at the pile top and the pile cross sectional area. The velocity at the pile depends on the cushion, energy losses in the hammer, the ratio of ram mass to anvil plus cap mass and in the case of Diesel hammers, on the hammer combustion chamber pressure before impact. Large portions of the hammer energy can be stored in the pile and the driving system without producing pile penetrations. Applications of energy formula, therefore, have to be considered sceptically even if the exact hammer energy is known.

3. The first stress peak at the pile top is dependent on input velocity and for all cases measured it is low for steel piles. If failure occurs at this time it can only be due to stress concentrations at the pile top caused by poor alignment of the driving system or irregular contact surface. In cases of rams that are heavy compared to the pile, large and potentially damaging stresses can occur if a stiff layer is contacted at the pile tip with little side resistance. High stresses then occur at the bottom and when the reflected wave returns to the top.

4. Due to their low velocity in easy driving, Diesel hammers should be less likely to damage concrete piles due to induced tension forces.

ACKNOWLEDGMENTS

Most of the data referred to herein was collected in a research project at Case Institute of Technology supported by the Ohio Department of Highways and the Federal Highway Administration. This project is primarily concerned with predicting pile capacity from dynamic measurements but the study and analysis of these measurements made possible the information on driving characteristics presented above. Therefore, the writers wish to acknowledge the support received from the aforementioned agencies.

The measurements presented in Fig. 9(*a*) were made for the A. Bentley and Sons Company, Toledo, Ohio, and their permission to use these data herein is acknowledged.

APPENDIX I.—REFERENCES

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APPENDIX II.—NOTATION

The following symbols are used in this paper:

A = pile cross-sectional area;
c = stress wave velocity;
E = Young's modulus;
E_k = kinetic energy;
E_m = manufacturer's rated energy;
E_n = reduced or net energy;
E_t = transferred energy;
ENTHRU = maximum of E_t (see Ref. 1, p. 129);
e = coefficient of restitution;
F_c = force between ram and block;
F_p = pile top force;
k = spring stiffness;
M_b = mass of block;
M_c = mass of hammer components plus pile;
M_r = mass of ram;
v_c = cushion top velocity;
v_i = ram impact velocity;
v_p = pile top velocity;
W_a = weight of cap plus anvil;

W_h = weight of ram, anvil and cap;
W_p = weight of pile;
α = pile to hammer mass ratio;
ρ = mass density;
σ_i = pile impact stress; and
σ_p = pile top stress.

9188 PERFORMANCE OF PILE DRIVING HAMMERS

KEY WORDS: Analysis; Blocks; **Construction**; Damages; Energy methods; **Foundations; Hammers**; Measurement; **Models; Pile drivers; Pile driving;** Waves

ABSTRACT: Using results from both theory and measurements the action and behavior of hammer-pile systems are considered. Three types of models are used to describe the behavior of a hammer-pile system. One is the wave solution of St. Venant for a pile struck by a rigid body. The two other models use a mass and a spring to describe the effects of blocks and cushions, respectively. The interpretation of measured quantities using such models allows conclusions to be drawn regarding the driving ability of a hammer, situations involving pile damage, energy losses and transfer and characteristics of certain measured quantities. As a result it is shown that the Michigan records were meaningful within the particular measuring system used and recommendations are given for a transducer design that allows the measurement of more meaningful quantities. Diesel hammer performance and energy output is analyzed and it is shown that these hammers perform adequately.

REFERENCE: Rausche, Frank, and Goble, George G., "Performance of Pile Driving Hammers," *Journal of the Construction Division,* ASCE, Vol. 98, No. CO2, **Proc. Paper 9188**, September, 1972, pp. 201-218