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Automatic signal matching with CAPWAP

F. Rausche & B. Robinson
Goble Rausche Likins and Associates Incorporated, Cleveland, Ohio, USA

L. Liang
Pile Dynamics Incorporated, Cleveland, Ohio, USA

ABSTRACT: CAPWAP® Provides the most reliable means of analyzing dynamic pile top force and velocity records from the Pile Analyzer® (PDA). This is a signal matching approach which requires that certain soil parameters are adjusted until measured and calculated pile top variables reach a reasonable match. The number of unknown soil parameters depends on the depth of pile penetration and therefore the computational effort can be appreciable if the pile is long. The process can be either done in an interactive manner or automatically with great time savings. Current practice requires that the automatic results are checked by interactive analysis.

In an attempt to make the automatic solution reliable, several additional matching parameters have been included in the CAPWAP model. Among these variables, the most important is the final set (inverse of blow count) of the hammer blow analyzed. Unfortunately, since restrike data is usually analyzed by CAPWAP for long term static capacity predictions, final set is not always accurately known. For this reason a study was undertaken to evaluate the accuracy of the automated CAPWAP results including blow count matching compared to the traditional approach. More than 30 cases where static load tests and restrike tests had been performed were analyzed using the automatic procedure provided by the Windows based CAPWAP Version 1999-1. This program also calculates the total dynamic resistance (the sum of damping and static resistance) allowing for an assessment of the ratio of total dynamic resistance to static resistance and its relationship with soil type.

1 INTRODUCTION

Dynamic pile testing has two distinctly different goals: (a) monitoring the installation of impact driven piles to avoid pile damage and assure sufficient pile penetration for bearing capacity at the time of installation and (b) dynamic load testing for an assessment of the long term bearing capacity of either a driven pile or a drilled shaft. The following paper deals with the analysis of dynamic load test records, i.e., force and velocity as a function of time.

Dynamic load testing requires measurement of pile top force and velocity and therefore the pile top displacement is also known. Because of stress wave effects caused by the rapid loading of the pile, a plot of measured force vs. measured displacement does not resemble the static load-set curve. For the calculation of the static load-set curve it is therefore necessary to reduce the dynamic force to a static one by removing dynamic effects of both pile and soil. This calculation is usually done by signal matching (Rausche et al., 1972) a process that has been continuously improved (Mure et al, 1983, Hannigan et al., 1987, Hussein et al., 1991). Today, CAPWAP (Goble Rausche Likins and Associates, Inc., 1999) is the most widely accepted computer program for the calculation of the static load set curve from dynamic test records. The latest version, a Windows program, includes a blow count matching option. This paper briefly describes the fundamental features of CAPWAP and presents a correlation study, which investigates the potential benefits of the expanded, automated search. The correlation utilizes information of GRL's data base which has been described by Thendean et al. (1996) in a paper that discussed the performance of an earlier CAPWAP version. The present paper also briefly investigates the relationship between total capacity and static capacity.

2 THE CAPWAP PROCEDURE

With two measurements at the pile top available, both input to and response of the pile top are known, however, one part of the system, the soil, which produces the response is unknown. In order to calculate the soil properties, a so-called inverse analysis has to be performed which identifies the unknown parameters of a soil model (Figure 1). This inverse analysis is commonly called a Signal Matching Analysis (Balthaus, 1986, Reiding et al., 1988), or a System Identification (Klingmüller, 1984). The solution has to be achieved iteratively: an assumption of the unknown soil parameters is made and tested by performing an analysis with one of the measured quantities as a top boundary condition. If there is disagreement between the other measurement and its calculated counterpart the calculation is repeated with a corrected set of soil model parameters. Obviously, the more realistic the soil model, the better its capability to match the measured quantities. On the other hand, a very sophisticated soil model may have too many unknowns and may not be uniquely defined by the matching process. For that reason, the relatively simple Smith soil model (Smith, 1960) has been most successfully employed for pile dynamic signal matching.

The traditional iterative matching procedure can be summarized as follows:

1. Data Input: select a record with appropriate energy and data quality
2. Data Check and adjustment (normally automatic)
3. Build pile model (normally automatic)
4. Check and change resistance distribution
5. Recheck data adjustment
6. Check damping parameters
7. Check quakes and unloading parameters
8. Find absolutely best match quality
9. Produce output

An important part of the matching procedure is the evaluation of the match quality, i.e. quantifying the difference between measured and computed quantity. In CAPWAP the match quality is the normalized, weighted sum of the absolute values of the differences between computed and measured values of all analyzed time steps. Normalization is achieved with respect to both maximum pile top force and the number of data points. The match over a 3 ms time period, following the first return of the stress wave from the pile toe, is given a double weight because of its importance for total capacity determination.

CAPWAP can either be used in an interactive mode or automatically. The automatic procedure searches for a best match using a step by step procedure that is also recommended to the analyst for interactive signal matching. In other words, the automatic CAPWAP is not a standard minimization software which would search in a more or less random manner for a set of soil parameters that produces a minimum difference between computed and measured pile top variable. Experience has shown that such a relatively mindless procedure may lead to unsatisfactory results. On the other hand, the automated CAPWAP procedure produces capacity results that are very similar to those obtained by experienced engineers working interactively on a computer. On occasion, however, the automatic method calculates an unsatisfactory resistance distribution near the pile toe. An experienced analyst must therefore always check the solution by means of additional trial analyses. For the simplification of the interactive matching task the CAPWAP program does provide difference minimization routines for individual soil resistance parameters.

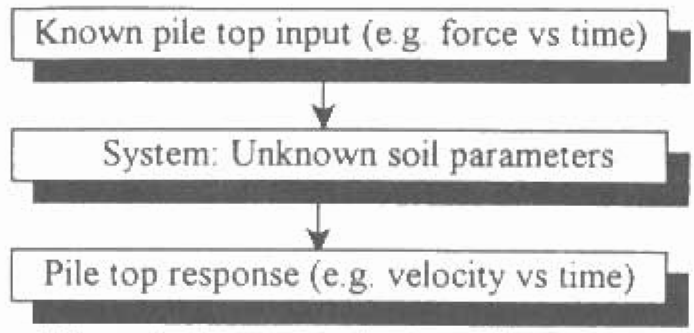

Figure 1. Inverse analysis problem

3 MATHEMATICAL MODEL

The pile is modeled as a series of uniform, elastic segments, typically 1 m long, of equal stress wave travel time. Calculations involve tracking the upward and downward traveling waves and their reflections where segment properties change or soil resistance effects exist. The simplicity and strictly elastic nature of this model is, unfortunately, a disadvantage when modeling non-linear or non-elastic situations such as cracks in concrete piles or certain types of mechanical pile splices.

The effect of the soil, resisting the pile motion, is modeled as a series of N lumped forces at intervals not greater than 2 m which depend on pile velocities and displacements. The parameters of this Smith soil model are the unknown quantities that CAPWAP must determine. In the standard analysis situation, the displacement dependent (static) resistance forces are represented by both a stiffness and a capacity value. The velocity dependent (dynamic) resistance forces are calculated using a damping factor. For the resistance forces acting on the shaft, soil stiffness and damping parameters are chosen proportional to the static capacity values and in this way, the number of shaft unknowns is kept to a manageable N + 2 values. For the toe an additional 3 unknowns have to be determined. To produce a good signal match over a long record time period several additional parameters had to be defined. The most important ones allow for a modification of the static soil stiffness and plastic limit (upward directed capacity) for the rebound phase of the pile and therefore have little or no effect on the calculated total static pile capacity.

Under certain conditions, particularly when the pile set under a hammer blow is very small, the assumption that soil resistance only depends on pile motion becomes inaccurate because the soil motion then has a magnitude comparable to that of the pile. The CAPWAP radiation model helps improve the calculated soil model for such cases by representing the soil surrounding the pile by a mass and a dashpot (Likins et al, 1996)

4 DATA CHECK (RECORD LENGTH AND SET MATCH)

In earlier versions of CAPWAP, the analyzed record length was generally set to 25 ms after the first return of the impact wave from the pile toe. This relatively short record length saved computer time but did not always allow for an accurate calculation of the final set. Today modern personal computers and more sophisticated operating systems provide the analyst with high computational speeds and huge memory space at a low cost. It has therefore become possible to economically analyze dynamic pile records over longer time periods and to perform many more trial analyses for more reliable results. The longer analysis time period assures that the calculation can be carried out until the pile stops moving, i.e. until the pile velocity becomes zero and the displacement has reached the final set. To be sure, the recommendation for Pile Driving Analyzer® users is a record length of 200 ms for normal land piles. Figure 2 is the example of a pile top force, velocity and displacement record which includes major vibrations after 100 ms. The record also indicates a final displacement value that matches the pile set or the inverse of blow count.

Ideally, the pile top set per blow is verified by independent observation so that the double integration of the acceleration can be checked and, if necessary, corrected. This two point data check and adjustment process is automatically performed in CAPWAP by slightly shifting the zero line of the acceleration. This zero line shift starts at impact, has a somewhat higher magnitude for a few milliseconds and a lower magnitude over the remainder of the record. The magnitude of this zero line shift is only a small fraction of the maximum measured pile top acceleration.

5 NEW DEVELOPMENTS

With a record that correctly double integrates to final set and with computational speeds allowing for an analysis to final zero velocity at the end of the record, the final pile set or its inverse, the blow count, can be calculated for all segments of the pile. As long as the final set is the same for several

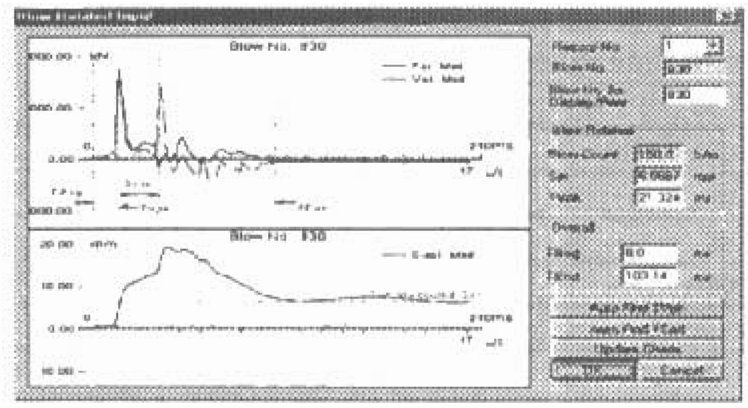

Figure 2. Typical force-velocity curves and displacement matching.

consecutive blows, this condition requires that all points along the pile achieve the same final set equal to that at the pile top. It is reasonable to require that the CAPWAP signal matching process also produces a match of calculated with observed pile top set; in other words, the average of all the sets of all segments equal the observed set. For lack of computing power this requirement had not been imposed on previous analyses. (It should be added that the most accurate method of calculating the final set of the pile is a residual stress analysis (RSA), which repeats the analysis several times thereby calculating the stresses locked into pile and soil. This analysis method is available as an option in CAPWAP. Regrettably, RSA is infrequently used because of its complexity.)

6 PROGRAM PERFORMANCE

The enhanced analysis procedure is available in the Windows based CAPWAP. To check whether or not the blow count matching (BCM) procedure would help improve the program performance, most of the data presented by Likins et al. (1996) was reanalyzed. The reanalysis involved adjustment of the acceleration values for both a zero final velocity and a final displacement matching the observed blow count at a later record time. The soil model parameters were then re-initialized to reset all soil parameters to the CAPWAP start up conditions. Any modifications to the pile profile were removed, the analysis count was reset to 1 and the initialized data file was saved. These steps assured the same results would be obtained as if the analysis had been started from the very beginning. With the reinitialized data file the automatic procedure was then run first with blow count matching and then again without blow count matching. The analyst did not interfere with the automatic analysis process in any way. Capacity, computed final set and match quality results were then subjected to a variety of correlation studies. As in the 1996 study, correlations were done using the ratio of CAPWAP divided by static load test capacity. Also, the time

Table 1. Calculated CAPWAP capacity divided by static load capacity at different time ratios

	BCM			No BCM		
Time Ratio	<.33	.33 - 1.25	>1.25	<.33	.33 - 1.25	>1.25
Min	0.57	0.62	0.50	0.41	0.56	0.51
Max	1.92	1.40	1.14	2.11	1.43	1.31
Mean	0.93	0.97	0.94	0.99	0.95	0.97
St Dev	0.28	0.17	0.19	0.40	0.19	0.24
COV	0.30	0.18	0.20	0.41	0.20	0.24
No. of Piles	26	37	11	26	37	11

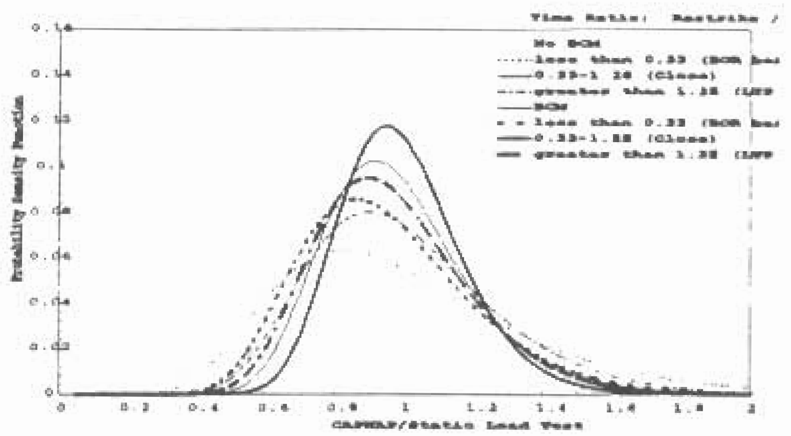

Figure 3 Log-normal probability density function for CAPWAP capacity

factor was introduced, i.e. time between restrike test and pile installation divided by time between load test and installation. Thus, a time factor less than one indicates that the dynamic load test was performed prior to the static test. For a meaningful correlation, the time factor should be close to unity. Indeed, Figure 3 and Table 1 show that the data marked "close" with time factors between 0.33 and 1.25 yielded the best correlations. For "No BCM" the mean was .95 and the coefficient of variation .20. Blow count matching (BCM) significantly improved the correlation to a mean of .97 with a COV or .18. Even the other time factor categories showed a clear gain in accuracy and precision.

7 QUALITY OF BLOW COUNT MATCH

Computed blow counts are presented in the form of histograms of calculated divided by observed final set (inverse of blow count) in Figure 4, both for "No BCM" and "BCM.". Clearly, the calculated sets improved although, in quite a few cases they did not change appreciably compared to those cases where blow count match was not attempted. It is concluded that either the observed blow count was not accurate - and since these are all restrike tests it would be expected that observed blow counts are generally inaccurate - or the dynamic data, the pile model or soil model did not accurately enough represent the test conditions.

8 MATCH QUALITY

Obviously, a number of automatic CAPWAP predictions are not satisfactory. In the data set under consideration, one prediction was nearly twice the static capacity and one was one half the static load test result. Ideally, the match quality number would reflect the reliability of prediction. In fact, Hannigan, et al. (1987) presented good correlations with one exception whose match was not satisfactory. It was therefore concluded that match quality is an indicator of the reliability of prediction. To further study the relationship between match quality and capacity prediction, Figure 5 was plotted which is normalized capacity vs. match quality. The cases presented were done with BCM; match qualities were therefore slightly higher than those achieved without BCM (BCM adds the final set error to the quality of the signal match.) Obviously, there is no correlation whatsoever between match quality and capacity prediction. However, it would be wrong to assume that match quality for a particular data set does not matter because for each case the program determined the best possible match or lowest MQ value. The match quality number for a particular case is therefore specific and may be used to judge the reliability of only that one data set. It is not possible to make a general requirement on match quality: in one case even an MQ = 24 yielded an acceptable result. However, it was probably more a matter of luck that a good correlation was achieved. In general, results with MQ > 5 should be considered with suspicion. In all cases the CAPWAP analyst must check the results calculated by the automated routine and determine whether or not additional MQ improvements are warranted and possible.

9 PREDICTED SOIL MODEL PARAMETERS

Table 2 presents damping and quake values calculated by either BCM or No BCM.. The mean values of the calculated shaft damping differed little (.74 vs .72 s/m), however, the blow count matching procedure produced less scatter (COV .49 vs .63).

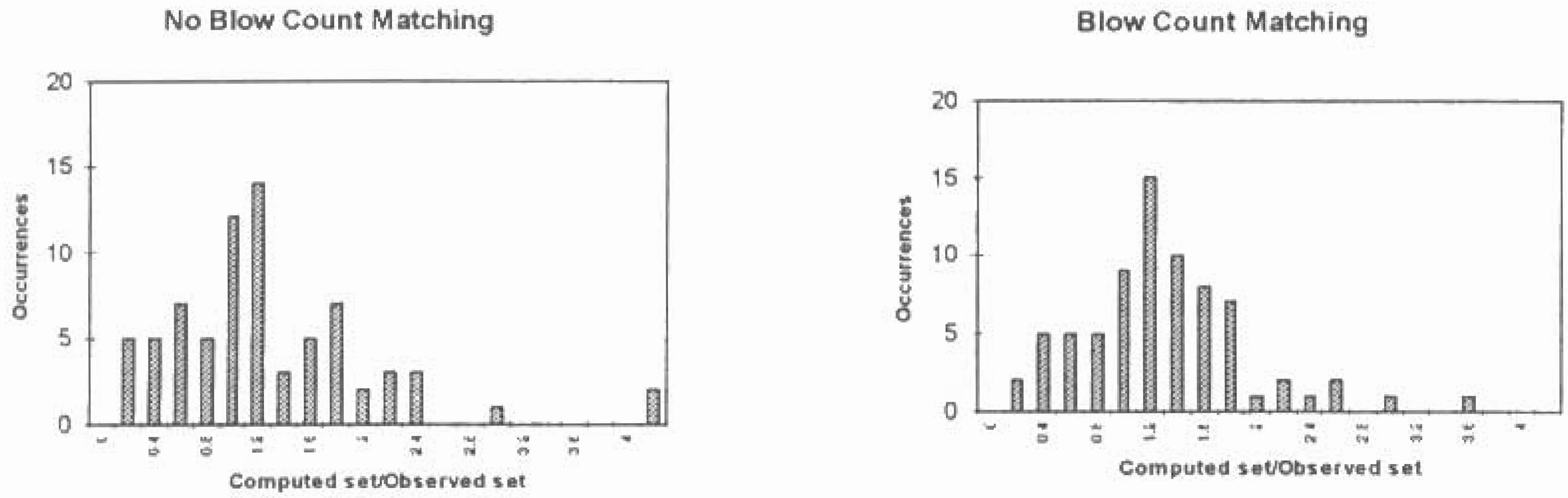

Figure 4. Computed to observed set comparison with and without blow count matching

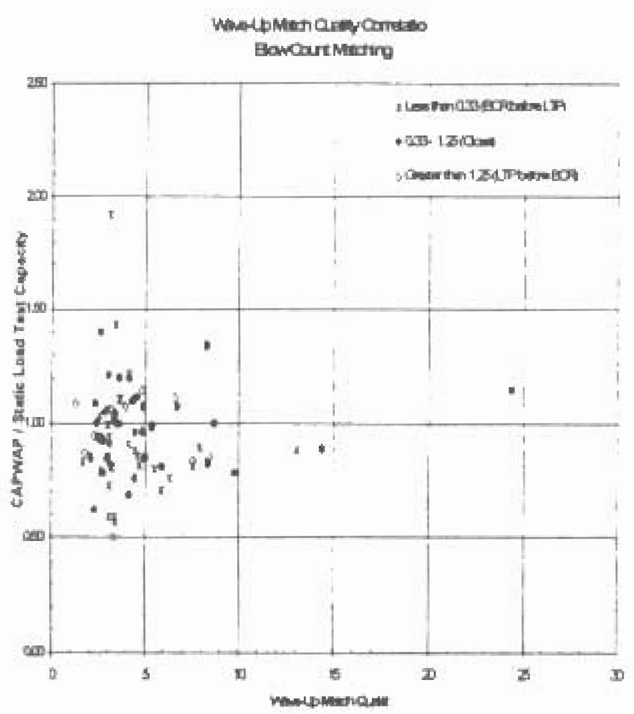

Figure 5. Match quality comparison with capacity prediction, blow count

This is not significant since the data represented a variety of soil types. Toe damping is generally assumed to be independent of soil type. Its magnitude is, however, highly dependent of the magnitude of end bearing since viscous damping is divided by toe resistance to produce the Smith damping value. The new CAPWAP routine produced much more reasonable results than the previous code with mean values of .84 vs 3.79 s/m and COV's of .99 vs 2.95.

Calculated quake values were non-dimensionalized by their GRLWEAP recommended values. Thus, a calculated skin quake of 2.5 mm would be presented as 1.0 as would be a toe quake value equal to D/120 (where D is the diameter or width of a displacement pile). The non-dimensional calculated shaft quakes were 1.00 and 1.17 for No BCM and BCM with a slightly greater scatter for the new calculation method, probably because variation of quake values often help to improve the blow count match. Toe quakes were very similar for the two calculation methods with mean non-dimensional values of approximately 2.0 (1.93 for BCM and 2.06 for No BCM) with significant scatter. This result matches the D/60 recommendation currently in GRLWEAP for certain types of soils.

Table 2 Dynamic soil parameter comparison

	Damping (s/m)		Quake	
	Shaft	Toe	Shaft/0.1in	Toe/(D/120)
No blow count matching				
Max	1.94	67.92	2.83	6.73
Min	0.13	0.00	0.39	0.28
Mean	0.72	3.79	0.99	2.06
St. Dev	0.46	11.19	0.45	1.33
COV	0.63	2.95	0.45	0.65
Blow count matching				
Max	1.85	4.56	2.97	6.72
Min	0.14	0.02	0.41	0.36
Mean	0.74	0.84	1.17	1.93
St Dev	0.36	0.83	0.56	1.32
COV	0.49	0.99	0.48	0.68

10 TOTAL, STATIC AND DYNAMIC RESISTANCE

CAPWAP calculates soil resistance as the sum of a static plus a damping resistance. The maximum static resistance component is equated to the static bearing capacity according to Smith (1950). Another approach would be the calculation of peak total resistance, i.e. the sum of maximum static plus peak dynamic resistance, multiplied by a reduction factor to account for dynamic resistance losses. A justification for this approach is the difficulty of separating static from dynamic components by signal matching when the pile displacements are small. The static, displacement dependent components then differ little from the damping, velocity dependent components which easily introduces errors in the calculation. Worse yet, in a hard or very dense soil or in a rock, the static toe resistance components sometimes appear to be velocity dependent and could therefore be misinterpreted as damping resistance by the traditional CAPWAP approach, leading to an underprediction of static capacity. To check for possible improvements in capacity prediction, various methods of interpretation of the total shaft and/or toe resistance values were explored. Table 3 shows the most promising method which adds the calculated static shaft resistance to the total, factored toe resistance. Sorting the results by dominant soil type, a marked improvement of the traditional approach was achieved for sands, where the mean of the ratio of predicted capacity to load test capacity would be 1.02 with a COV of 0.24. Further exploration of this method is warranted. However, at this time too little experience is available (only 14 cases for the sands) and the time factors should also be considered in future studies.

Table 3: CAPWAP static shaft resistance and total toe resistance divided by static load test capacity for different soil types

Soil Type	No. of Piles	Mean	St. Dev	COV
Clay	6	1.30	0.50	0.38
SandyClay	4	1.23	0.22	0.18
SiltyClay	8	1.08	0.20	0.18
Rock	6	1.15	0.18	0.15
Sand	14	1.02	0.25	0.24
ClayeySand	8	1.03	0.24	0.24
SiltySand	8	1.12	0.24	0.21
ClayeySilt/Silt	4	1.93	1.51	0.78
SandySilt	5	1.07	0.15	0.14

11 CONCLUSIONS

The correlation between CAPWAP predicted pile bearing capacity and static load test capacity can be improved if not only the difference between computed and calculated pile top quantity but also the difference between calculated and observed blow count is included in the match quality evaluation. The improvement over the traditional method, which ignored the calculated blow count, is significant and since, with modern computers, the additional computational effort is minor, blow count matching should always be done. Great care should be taken in the measurement of restrike blow count. It is believed that lack of accurate blow count measurement limited the improvement over the traditional CAPWAP approach. On the other hand, the signal matching process itself already incorporates blow count matching to a certain degree, since the measured velocity and therefore the top displacement are imposed as top boundary conditions. The improvement achieved with the new CAPWAP program should therefore be primarily attributed to a more accurate analysis over a longer time period.

As in earlier correlation studies, the time factor (time between load testing and installation divided by time between restriking and installation) proved to have the greatest effect on the accuracy of the CAPWAP prediction. Obviously waiting times comparable to those of the static test assures the best possible prediction of long term bearing capacity by CAPWAP.

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