Proven Success For Driven Pile Foundations

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Abstract

Over the past several years, a seven-step process has been developed for selecting driving criteria that has proven to be a successful formula for the installation of driven piles. The process incorporates static pile capacity estimates, wave equation analyses, pile driving analyzer use, and static load testing in a rational and consistent sequence, and has resulted in reliable and cost-effective driving criteria. The process has been used successfully for relatively small projects, but most frequently on projects that include a hundred to several thousand piles. Experience with this process on many projects has resulted in a 100 percent success rate in static load testing, with measured factors of safety between 2.5 and 3.0, avoiding excessive conservatism in design and unnecessary cost.

Introduction

The need for deep foundations on any project typically results from many factors, including subsurface conditions, foundation loads, and allowable foundation settlement criteria. Once a decision is made to use deep foundations—in particular, driven piles—the next step is the selection of the type of pile to be used and the design of the pile. Selection of the pile type, in addition to local experience and practice, is frequently based on subsurface conditions, while the preliminary choice of pile size and length is usually determined by static pile capacity calculations. The next decision is how the pile should be driven, including the selection of the pile driving system and the driving criteria. Accurate selection of the driving criteria will not only affect the reliability of the pile foundation, but can also greatly affect the overall cost of installation of the piles.

Many methods are available to determine the appropriate driving criteria. This paper discusses a process that has proven successful, resulting in reliable foundation design. We should note that the majority of the projects included in the paper are power plants with costs ranging from $300 million to more than $500 million. Hopefully, we will demonstrate that the process discussed here is valid and useful not only on projects of this size, but also for moderately small projects where driven piles are used for foundation support.

Pile Driving Criterion

In its simplest form, a pile-driving criterion is defined as a specified pile-driving resistance when the driving operation can be stopped. The criterion in the United States is generally expressed in a minimum number of blows per foot or blows per inch. In other parts of the world the criterion is expressed in SI units, typically as a minimum number of blows per 250 mm or 300 mm. Less commonly, the driving criterion is expressed as less than a defined movement for a specified number of blows. The desired result is to establish a mechanism that insures a driven pile will have adequate capacity with a reasonable factor of safety.

Understating the driving criterion can result in a pile with less than adequate capacity. Overstating the driving criterion can mean that the pile will be unnecessarily driven to a higher resistance and depth, generally resulting in additional cost to the project, and impact on schedule. Over-driving can also result in damage to the pile. Selection of the right criterion helps to achieve a successful project in terms of both safety and cost.

The Process

There are different methods available for the selection of a pile-driving criterion, including dynamic pile-driving formulae, wave equation analyses, and evaluation of static and dynamic load tests. Any of these methods, if used properly, can result in the determination of a valid driving criterion. Although the process outlined here contains no new tools or unique methods, it details a method to simply link and combine several established tools to optimize the final driving criterion selected. The steps of the process are:

1. Evaluate subsurface data and perform static pile capacity analysis.
2. Select preliminary driving criterion using “wave equation” analysis.
3. Drive probe (or indicator) piles across the site area using a pile driving analyzer (PDA) to evaluate capacity, driving stresses, and hammer performance, including retapping of selected piles after initial set-up.
4. Evaluate and adjust the driving criterion based on the results of the PDA.
5. Drive static test pile(s) using the revised driving criterion.
6. Load test the test pile(s).
7. Perform a final evaluation of the driving criterion for the production piles based on the load test results.

A detailed discussion of each step is included below.

Evaluate Subsurface Data and Perform Static Pile Capacity Analysis. It is essential to have adequate subsurface data, regardless of the type of foundation or ground improvement to be used. Without having a reasonable subsurface investigation with a sufficient number of exploration points, along with an adequate laboratory testing program, the remaining steps in this process are greatly compromised.

Once the subsurface data are available, the engineering study for the project is started. The decision to use piles typically results from having soft/loose soil conditions near the surface that would result in unacceptable settlement or inadequate bearing capacity for shallow foundations. The next step is to perform a static pile capacity analysis. Before we can proceed with this, we need to have some idea of the pile loading, not only in compression but also in tension and lateral loading to select the type and size, or range of types and sizes, of pile to be analyzed. Obviously, the loading per pile will depend on the number of piles selected per foundation. For driven piles for major power plant foundations, we have found that compressive capacities in the 750 to 1200 kN range result in economies in pile cap design. This typically defines the driven pile size—normally in the 300 to 400 mm diameter range for these loads. The type of pile selected is governed mainly by cost and availability, as well as local practice. However, the loads can also influence this selection process—displacement piles will provide more skin friction and thus accommodate larger uplift loading, while piles with high bending stiffness values (elastic modulus times moment of inertia) provide larger lateral resistance. The static analysis often determines that several types of pile will be acceptable for a given project, such as precast concrete, pipe piles, shell piles, or H-pile sections.

There are numerous methods for performing static pile capacity analysis, using either hand calculations or available computer software. The static analysis is the starting point in the procedure and is rarely used as the final determination of the pile capacity for a project. In many cases pile capacity estimates based on static analysis are conducted and issued as preliminary calculations until the entire design procedure can be completed. It is still important to provide as accurate an evaluation as possible at this point because the static analysis usually forms the basis for the cost estimate and later bidding of the piling for a project. In addition, the static analysis and resulting cost estimate are often used for comparison with other alternatives, such as some method of ground improvement, to determine if piling is the most economical solution.

The static analysis provides an estimate of ultimate pile capacity. Factors of safety are applied to obtain allowable or design capacity. Safety factors of 2 on skin friction and 3 on end bearing are commonly used. It is also equally important to ensure the design will perform within acceptable levels of settlement. This is typically as far as we would proceed with a pile foundation design during the estimating stage of a project.

Select Preliminary Driving Criteria and Hammer Energy from Wave Equation Analysis. If the project bid is successful, the next step would be to issue a pile bid package. As indicated above, there may be a single pile type or numerous pile types included in the bid package, often with the option for the contractor to provide an alternative type. In addition to including the pile parameters (dimension, capacity, and estimated length) in the bid package, a range of the required driving energy for the pile hammer is typically provided. This is done to insure that the contractor has the right equipment available to do the work. To estimate this driving energy, a preliminary wave equation analysis is performed. At this time, since the actual details of the piles and pile driving systems are unknown, it is necessary to make some assumptions in performing this preliminary analysis. These include details of the hammer and driving system (driving helmets, pile cushions, pile efficiency, etc.).

One of the goals of the preliminary wave equation analysis is to find the right range of driving energy to make sure that the pile is not damaged during driving (oversized hammer) or that the total driving time needed to achieve the required capacity is not unreasonable, and that the required capacity can actually be achieved (undersized hammer). The wave equation analysis provides an estimate of pile stress during driving. For steel piles, only compressive stresses need be evaluated, while both compressive and tension stresses need to be checked for concrete piles. Part of this process also includes selecting a factor of safety for the required ultimate capacity (R_{ult}) obtained from the wave equation analysis based on the pile design allowable loading. We commonly apply a factor of safety to R_{ult} of between 2 and 2.5. We typically repeat these steps in the process for each type of pile included in the bid package and for several types and models of pile hammer. Again, it is important to note that everything to this stage has been classified as "preliminary" since sufficient information is still not available to make the final design selection.

As indicated, the results of the static analysis and initial wave equation analysis are used in the bid package for the piling contract. After the bidding is completed and a contractor has been selected, we can determine the actual driving system that will be used for the project. The selected contractor is requested to supply the details of his available driving equipment, including details of the hammer, hammer system, and pile driving cushion(s) proposed for the project. It is important that, once the decision is made to use a particular hammer for a given project, changing the hammer should not be allowed except under extreme circumstances. As will be discussed in more detail below, even replacing the hammer with the same model during production can be undesirable. With the data provided by the contractor, the initial wave equation analysis is modified to incorporate the actual equipment that will be used, and the preliminary driving criterion for the project is established. Again, during this process it is necessary to select an appropriate factor of safety, typically in the range of 2 to 2.5, and to verify the driving stresses are within acceptable ranges.

Shown in Figure 1 is the standard printout from a wave equation program, in this case for a project using steel H-piles and a Delmag D30 diesel hammer. We have a pile with a design capacity of 1,000 kN and a corresponding R_{ult} of 2,500 kN using a 2.5 factor of safety. Based on these results, a preliminary driving criterion of about 89 blows per 300 mm would be selected for this project. It is important at this stage to check that the selected driving criterion is not in the flat or horizontal portion of the curve, because at that point little additional capacity can be achieved and time and money will be wasted driving the pile beyond that point on the curve. It is also common practice to require that the driving criterion be met for up to 3 consecutive increments of 300 mm to make sure that the pile is well seated in the bearing layer, especially when driving a pile to a refusal condition. Driving criteria can also include minimum tip elevations when piles are being designed to carry tension and lateral loads in addition to axial compression loads. The printout also shows the stresses that are expected to be developed in the pile during driving. These results must be checked to verify the pile will not be overstressed during driving.

At this time we have a pile contractor, pile type, and preliminary driving criteria selected, and are now ready to start the actual work.

Drive Probe Piles. Up to this point, the work has been limited to desktop studies in the office. It is now time to move to the site. At this stage, for a large piling project, we would select 10 to 20 locations across the site to drive probe (or indicator) piles. Driving probe piles has several goals, including determining how the piles actually drive on the site as compared to the predictions of the preliminary analyses, especially since subsurface conditions almost inevitably vary, and to evaluate the driving system being supplied by the pile driving contractor. The probe piles can be either production piles or pre-production piles not used for production. Use as production piles can save money, but requires that the foundation design be far enough along to accurately define pile placement, and that there is a high degree of confidence that the probe piles will have sufficient capacity based on the subsequent pile load testing.

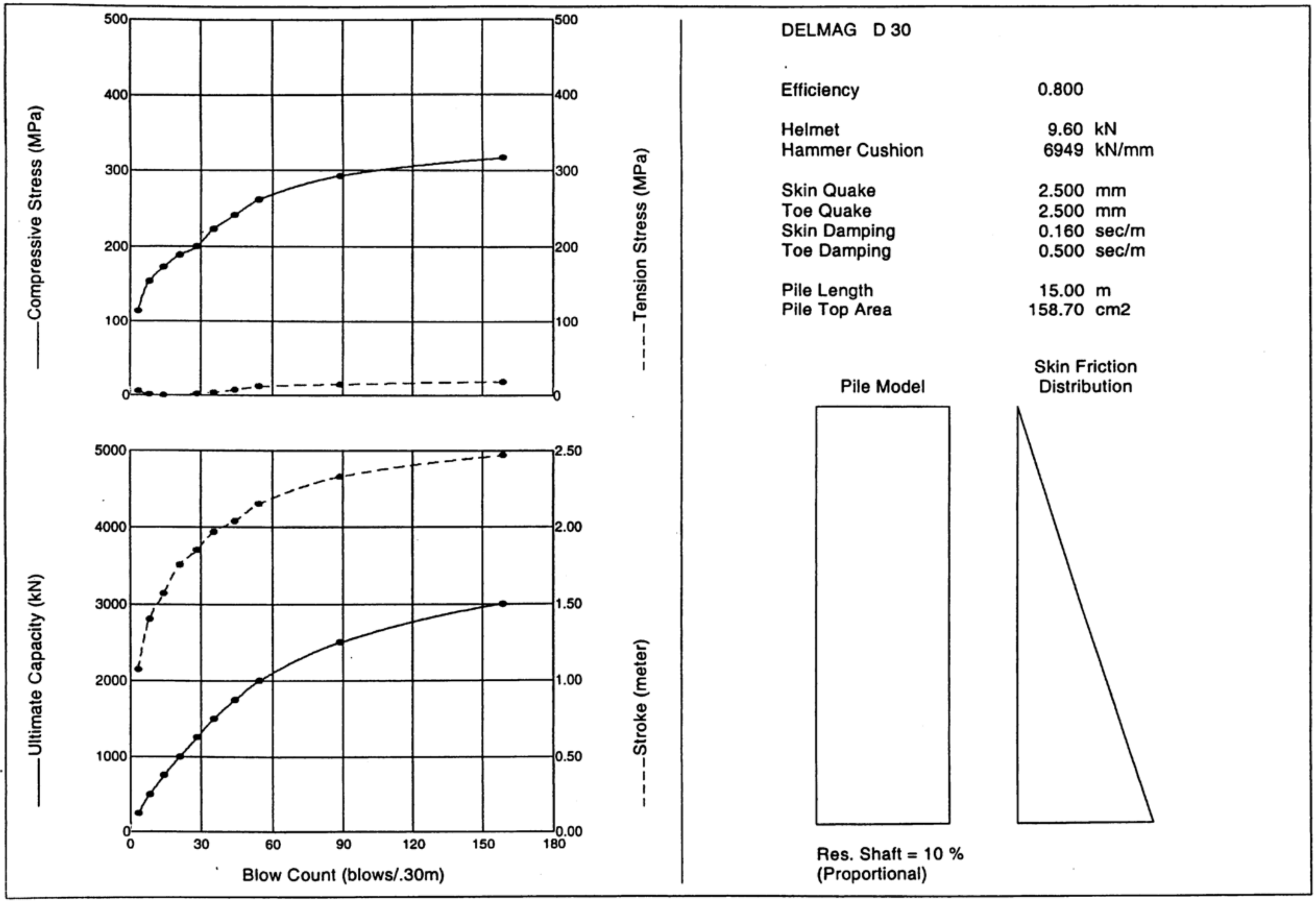

Figure 1. Typical Wave Equation Printout

The first goal at this time is to verify that the pile driving criteria can be achieved with the pile driving equipment and the selected pile, and, perhaps most importantly, using the length of pile estimated from the original static calculations, and thus maintaining the estimated cost. The probe piles can also be used as a good indicator of the range of pile lengths that will be required for all the production piles. This is particularly important if precast concrete piles are to be used for the project.

A second goal of the probe pile program is to allow verification of the pile driving system being supplied by the contractor. This is typically done using a pile driving analyzer (PDA) during driving of some or all of the probe piles. By using the PDA, accurate estimates can be made of the driving energy going into the pile and the actual driving stresses in the pile, and a more precise evaluation of the ultimate pile capacity can be achieved. The estimate of the driving energy going into the pile is very significant since the efficiency of any pile hammer varies considerably. This variation in efficiency depends not only on the make and model of the hammer, which are known parameters, but, equally importantly, on the maintenance of the hammer. We have found the efficiency of hammers to vary from as high as 85 percent to as low as 33 percent. If we are unaware that a hammer is operating at very low efficiency, the subsequent test piles could be driven with entirely inadequate criteria, quite possibly resulting in a failing pile load test. This failing test would have to be repeated, causing time delays to the project and additional costs.

We also recommend that PDA be repeated on several of the probe piles as part of a retap program to determine if either pile setup (freeze) is occurring or some relaxation has resulted with time. Although it is usually best to wait about a week before conducting a retap program, it is more typical to wait only two to three days or even less, since pile driving is almost always controlled by schedule. Being able to measure pile freeze is particularly important when driving piles that will develop capacity in skin friction in cohesive soils, where much of the initial pile driving resistance has been lost due to pore pressure buildup and shear failure from the driving. It is also important not to allow final cut off of the probe piles until the final driving criteria are established, in case it becomes necessary to redrive these piles.

Evaluate and Adjust the Driving Criteria Based on the PDA. In a perfect world, the results of the PDA would precisely match the initial static calculations and wave equation analysis. Since we do not live in a perfect world, it is important at this time that the results of the PDA testing be evaluated against the preliminary analyses. The purpose of this verification is to determine if adjustments are necessary to the driving criteria to be used for the next stage of the project, namely driving the test piles. During this stage of the process, the R_{ult} determined from the wave equation analysis and the PDA should be compared to see if similar results are being obtained. We have typically found that if the R_{ult} from the PDA is less than that predicted from the wave equation analysis, the actual pile hammer efficiency is less than that originally assumed. Once the pile hammer efficiency adjustment is made to the wave equation analysis, close agreement generally can be achieved between the two.

When analyzing the PDA results for capacity, the data are usually evaluated by CAPWAP, which is a signal matching process that extracts the resistance distribution and soil behavior such as damping and stiffness from the measurement. The soil model can be used to improve the refined wave equation analysis results. CAPWAP can provide a simulated static load test as an important and useful element of the analysis. Upon completion of the review of all available data, adjusted driving criteria can be determined and used with a high degree of confidence in the next stage of the process, i.e., driving the test piles.

Drive Test Piles for Static Load Testing. Many will argue that using static load testing in addition to running PDA is overkill in the process, but at this time, at least for large piling projects, we always conduct static load testing in addition to PDA testing. (On many projects we will reduce the number of static load tests in conjunction with the PDA. However, static load tests are still required by many building codes.) The test piles are driven at various locations across the site using the adjusted driving criteria. We also typically monitor the test pile driving using PDA to confirm the pile driving system characteristics and the predicted R_{ult} against the pile capacity that will be measured from the static load test.

Static Load Testing. The static axial compressive load testing on each project is performed in general accordance with ASTM D 1143 (ASTM) using either the standard or the quick load test procedure. The load testing is typically conducted to three times the allowable design loading or to failure, whichever occurs first. (Typical code requirements are to load the pile to twice the design load.) Once the load testing, which typically includes a minimum of 2 to 3 piles, is completed, the results are evaluated to determine the ultimate pile capacity. There are many methods available in the literature to estimate the ultimate pile capacity from the load test results. The allowable capacity is then determined by applying a factor of safety to this ultimate capacity. The Standard Guidelines for the Design and Installation of Pile Foundations, 20-96 by the American Society of Civil Engineers (ASCE) provides recommendations for factors of safety that are dependent on the level of site investigations and testing, as shown in Table 1. As can be seen from Table 1, if the entire process as outlined in this paper is followed, the lowest factors of safety recommended by Manual 20-96 can be applied to the design.

Table 1. Partial Safety Factors F_1

Capacity Determination Method	Design Axial Loads			
	< 133 kN (<15 Tons)	142- 356 kN (16 – 40 Tons)	364 – 889 kN (41 – 100 Tons)	> 889 kN (> 100 Tons)
From Pile Load Test Coupled With Wave Equation And Static Analysis	1.5	1.5	1.6	1.8
From Dynamic Measurements Coupled With Wave Equation And Static Analysis	1.5	1.6	1.7	2.0
From Wave Equation And Static Analysis	1.5	1.8	1.9	N/A
From Driving Formulas And/ Or Static Analysis Or Other Method	1.5	2.0	N/A	N/A

Perform Final Evaluation of Driving Criteria for Production Piles. The results of the static load testing are compared with the results of the static analysis, the wave equation analysis, and the PDA. If good agreement exists between all of these, the driving criteria established for the test piles are then adopted for use for all production piles, and production driving can be started. If the static load test results do not agree with the analyses, then the option is to adjust the driving criteria either upward or downward. The driving criteria will be adjusted upward if the load test showed less capacity than required and may be adjusted downward if the load test showed more capacity. Adjusting the driving criteria at this point is always a concern, since it is difficult from a cost and schedule standpoint to perform additional load testing on piles driven to the adjusted criteria. Slight adjustments can easily be justified and verified by additional wave equation analysis. If the load test results prove to be significantly different from the results of the wave equation analysis and PDA, it may be necessary to restart the process. For numerous projects over the past decade or more, we have never found it necessary to restart the process.

Additional Notes

Unfortunately the process does not always stop at this point. Despite the best efforts and a carefully thought out and well planned design procedure, things can change during production driving that will cause havoc with the driving criteria. The two most common problems are unanticipated variations in subsurface conditions, and changes in the characteristics of the pile driving system. Piles driven short can occur as a result of changes in the subsurface conditions or densification of the soils from the pile driving, especially piles driven with close spacing in granular soils. If piles are being driven short, additional PDA can be conducted to evaluate their capacity. Based on the results of the PDA, the piles can be accepted unless the minimum tip elevations required for tension or lateral capacities have not been obtained. A problem with shorter than anticipated prestressed precast concrete piles is that cut off can leave insufficient reinforcement for lateral capacity. If soil conditions are poorer than expected at planned tip elevation, the piles will drive longer than anticipated. This can be a particular problem for piles that are difficult to splice, notably prestressed precast concrete piles.

The other major problem that can occur during production driving is a change in the characteristics of the pile driving system. This may result from reusing pile cushions for too many piles, especially plywood cushions for precast concrete piles, or simply from wear and tear from the continuous operation of the hammer. It is a fact of life that pile hammers are mechanical pieces of equipment whose characteristics change with use. Hopefully these changes are minor during a given project and do not affect the driving criteria over the period of driving. Things to watch for are fairly obvious, such as a change of the hammer during production driving or even maintenance of the hammer. Change of hammer should not be allowed during a project unless it is unavoidable, e.g., the hammer should not be changed simply to suit the contractor’s workload or schedule. Even if the replacement hammer is of the same make and model, the driving energy can be significantly different. PDA can be justified on larger piling jobs to qualify additional hammers.

The simple maintenance of a hammer can also change the driving energy appreciably. As an example, on a project in Egypt, the contractor replaced the compression rings in the open-ended diesel hammer during the down time for load testing and prior to production driving. This maintenance to the hammer more than doubled the driving energy to the pile. This change, if not detected by PDA, would have caused all of the piles to be significantly overdriven. On a more recent job in Taiwan, the PDA during the probe pile installation indicated that the variable stroke hydraulic hammer was only operating at about 33 percent efficiency. The piling contractor contacted the hammer manufacturer who suggested a series of maintenance items that should be conducted on the hammer. However, since driving the probe and test piles had been completed, and sufficient energy could be achieved by using a higher stroke setting, it was decided not to allow the contractor to perform the maintenance until after all the production piles were driven.

Even if no changes are made in equipment or no maintenance is performed, changes to the characteristics of the hammer can occur that cannot be detected visibly but can significantly affect the energy transfer to the pile. The best method for evaluating these potential changes during production driving is to conduct additional PDA testing. It is our general policy to allow for about 5 percent of the production piles to be tested using PDA. If required, adjustments in the driving criteria can be made at this point.

Summary and Conclusions

As stated earlier, there are no new techniques presented in this paper on how to have a successful driven pile project. However, we hope that some benefit can be gained from summarizing the various established steps as a single coherent process. Many would argue that on smaller projects the process outlined above would be cost prohibitive and too time consuming. Obviously this is true where only a handful of piles are needed. However, the process is applicable to moderately small projects, particularly where the piles are spread over a relatively extensive area.

We have had considerable success with this process, and, fortunately, have not experienced a pile project where there has been a pile failure or settlement of a structure beyond levels anticipated. The process has been and can be applied to any type of driven pile (precast concrete, steel pipe, steel H-pile, and shell piles). In addition, by using all or even some of the steps in the process, a high level of confidence in the results can be obtained, allowing for the use of lower factors of safety. This will reduce the overall cost of the piling and the overall time required for installing the piles, which can quickly and easily outweigh the cost of following this process. In conclusion, and most importantly, sound, experienced engineering knowledge and judgment must be applied to every step of this process to insure success.

References

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