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RESPONSE SPECTRA FOR EXPLOSION RESISTANT DESIGN AND ASSESSMENT

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ABSTRACT

This paper describes a project to examine the explosion test results obtained at Spadeadam in the 1990's from the point of view of structural response.

At an early project phase, when reliable simulations may not be available, nominal explosion overpressures and durations or past experience from similar situations may be used as inputs to the Response Spectrum approach. The results, however, will only be as accurate as the estimated loading.

Structural engineers are often presented with complex pressure traces and are expected to design efficient structures to resist these loads without any further guidance.

Response surfaces, representing peak deflection against scaled natural period and structural resistances, have been calculated for a large number of experimental and simulated pressure traces. Biggs response curves are a special case corresponding to triangular loading time histories.

The Response Spectra are obtained from these response surfaces by taking horizontal sections of these surfaces at allowable ductility values.

The required static resistance for a structure with a given natural period and pre-determined allowable ductility may be read from these curves. The design or assessment may then proceed with this required static resistance which may be re-interpreted as an equivalent static load.

The project team has had access to FLACS simulated pressure traces corresponding to the Spadeadam tests. This has enabled a comparison to be made between experimental and simulated traces taking into account the target structures' characteristics. A description of the method has been included in reference [1], in the Commentary of the new API RP on Fire and Blast which will be made available during 2006, and in a forthcoming OTO (HSE) report.

INTRODUCTION

Objectives

The main objective of the project was to derive static design pressures for sizing main structures and barriers.

BP supplied the FLACS simulated pressure traces corresponding to the experimental results obtained at the Spadeadam test site during the 1990's.

Generation of response spectra for the experimental and simulated results has given a more robust measure of the conservatism or otherwise of the simulation traces than simple comparison of peak pressures would yield.

Motivation

Currently, explosion loads can only be specified realistically towards the end of detailed design when the final detailed geometry is known. This has led to late design modifications and project delays.

Structural engineers are presented with complex simulated or experimental pressure traces and are expected to design efficient structures to resist these loads. It is usually desirable to allow significant local plastic deformation in order to arrive at an efficient design. This often results in the need for a non-linear, dynamic design approach which may be expensive and can be prone to error.

Historical Overview

It is now twelve years since the results of Phase 1 of the Joint Industry Project on 'Blast and Fire Engineering for Topsides Structures' gave rise to the Interim Guidance Notes [2] where the Biggs method [3] was described. Since 1992, approximately £40 million has been spent on research and testing, resulting in significant technological developments, particularly in the areas of fire and explosion loading. As a result of this work it was appreciated that the extreme event cannot always be designed against.

A probabilistic approach [4] has enabled explosion loads to be derived which **can and should be designed against**. The two level approach involving two levels of explosion design loads was developed during consultation with industry in the development of the OKOOA/HSE Guidance [5]. The lower level of Design load, the strength level blast (SLB) was proposed as a confirmatory check using conventional elastic structural response techniques. This was defined on a probabilistic basis.

More recently the new API RP on fire and blast [6], expected to be released later in 2006, gives a number of nominal overpressures to be used as a guide for the load levels to be expected. These values are intended to be used particularly at an early project phase when reliable information on load levels may not be available.

The disadvantage of the nominal overpressure values is that the dynamic properties and reserves of strength of the target structures are not represented. The Response Spectrum approach described in this paper overcomes these difficulties and gives the load levels appropriate for the SLB design case without recourse to probabilistic arguments.

The response spectrum approach has been routinely applied in the area of earthquake structural assessment for a number of decades [7] and was originally applied in the Second World War to represent ground effects from high explosives.

NOMENCLATURE

T = Natural period – the time required for a freely vibrating structure to complete one cycle of motion. (secs)
μ = Ductility – The ratio of peak deflection to the deflection at first effective yield (also appears in some figures as Mu)
td = Load duration (secs)
I^+ = Positive impulse of pressure trace up to the first intercept with the axis after the peak.
R = Resistance at effective yield (mbar)
Xe = Deflection at first effective yield.
Pe = Effective pressure in a pressure trace (mbar) (=$2I^+$/td)
Ppeak = Peak pressure from pressure trace (mbar)
Pstat = Equivalent static Design pressure
Sf = Shape factor for pressure trace (=Ppeak/Pe)
DLF = Dynamic load factor (R/Pe)

THE USE OF RESPONSE SPECTRA

A Response Spectrum may be constructed from the classic Biggs response charts if a triangular load time history is a good representation. In this paper actual experimental and simulated pressure traces are used to construct the spectra.

Figure 1, at the end of this paper, illustrates how Response Spectra are used in the determination of the required static resistance of the target structure. This is equal to the static Design pressure.

Structural idealization

The structural element to be assessed may be a panel, a deck, module or a whole topside if they can be idealized as a one degree of system oscillator. This process will be familiar to designers who use the Biggs response method [3] and is in routine use.

The effective mass Me and stiffness Ke of the structure and the effective yield deflection Xe are calculated. This enables the natural period T to be calculated from:-

$$T = 2\pi\sqrt{\frac{Me}{Ke}}$$

and the static resistance to be calculated from:-

$$R = KeXe$$

Allowable ductility

The next stage is to assess the allowable ductility for the structural element. The allowable ductility of a structural element is a measure of the amount of deformation the element can sustain before rupture or when its performance standards cease to be satisfied. This is usually expressed as a multiple 'μ' of the effective elastic yield displacement.

In explosion response, an allowable ductility may be associated with a particular structural type or configuration.

The allowable ductility is assessed for the structure by consideration of the connection detailing and framing. The allowable ductility may also be derived from a known reserve strength ratio in combination with the performance standards appropriate for the situation.

For example, small allowable displacements (μ ~1) are appropriate for the Temporary Refuge and supports of critical systems. Large allowable deformations (μ ~5 to 10) may be allowed for in the performance standards for equipment and piping supports, cladding and blast walls. A larger allowable ductility will often give rise to a more efficient design.

Load duration and magnitude

Determine the load duration td and the effective pressure Pe from the available loading information. The explosion loading may be determined from local conditions by the use of nominal overpressures, previous experience, risk classification, simulations or experiment.

The method of determining td and Pe from experimental or simulated pressure traces (time histories) is described later in this paper.

Example implementation

Once these parameters have been assembled the appropriate response spectrum may be used (Figure 1).

Consider an element with an allowable ductility of 2. The correct curve in Figure 1 may then be selected.

If the natural period turned out to be half the load duration (td/T=2) then the MU=2 curve would yield R/Pe=1.15. This means that the required static resistance is 1.15 times the effective pressure Pe indicated by the corresponding value on the vertical axis. Pe is also equal to the equivalent static design load. For a trace with Pe = 1000 mbar (1 bar) the required resistance for the target structure would be 1150 mbar. This can immediately be compared with the calculated value of R.

A static elastic analysis with a blanket load of 1150 mbar could then be performed to assess the structure in the normal way. This approach reduces the explosion capacity check to the level of a conventional load case similar to those performed for static dead loads, live loads and environmental loads.

It should be borne in mind that an explosion is an accidental load, the full yield strength may be used including the benefit of strain rate effects. This would be taken into account by allowing a larger utilisation factor in the code checks [5].

Regard should, however, be paid to re-bound effects and other dimensional constraints laid down in the performance standards. Heavy process equipment on support structures is particularly susceptible to these effects.

EXPERIMENTAL EXPLOSION PRESSURE TRACES

Spadeadam tests

A large number of full scale explosion tests were carried out at the Spadeadam test site in the UK between 1990 and 2002. These explosion events were also simulated using the Computational Fluid Dynamics (CFD) predictive code FLACS [8]. Direct comparison of simulated and experimental pressure time histories has been inconclusive.

The test results contained a large number of short duration 'spikes' superimposed on a generally smooth curve, of a form similar to the typical pressure time history shown in Figure 2 at the end of this paper.

Whatever the cause of these spikes, investigations have shown that the influence of these short duration loads is insignificant for structural components with natural periods more than 0.02 seconds (natural frequency less than 50 Hz) - which includes most components.

These spikes, which can take the observed peak overpressure Ppeak beyond 12 bar, make Ppeak an unreliable measure of explosion severity.

Pe is a measure of the severity of the pressure trace which is based on the positive impulse and is independent of the precise shape of the trace. The duration, td is also derived from the trace by considering the cumulative impulse of the trace.

Representation of load severity.

Impulse, defined as the integral under the pressure trace, is an important measurement for explosion structural response and is an averaged measure as it includes all data in the pressure-time history. There is also a more consistent correlation between impulses for actual test results and CFD simulations.

Measures of load duration 'td' have been found useful in scaling the target structure's natural period on the horizontal axis of the Biggs response curves and Response Spectra.

Figure 2 illustrates the difficulties in attaching a meaningful value to this measure for experimental traces but two main options are available.

A more rigorous approach, tailored towards actual experimental and simulated traces is shown in Figure 3. This method was originally presented in reference 9.

The graph shows the accumulated impulse to time t for a realistic pressure trace. The 'spikes' in the original curve are smoothed by the process of integration and do not appear in the graph.

The start time of the pressure pulse 'tstart' is assumed to be the time at which the positive impulse reaches about 5% of the peak value. This is because pressure traces often have an extended lead phase where the pressure is negligible whilst the explosion is developing.

The time at which the pressure trace effectively crosses the axis is given by the time of maximum impulse 'tend' on the graph.

These times may be extracted automatically and the difference is taken to be the load duration 'td'.

Once an effective duration has been established, response spectra may be plotted in terms of td/T as is the case for the Biggs approach.

The effective peak pressure Pe is then calculated directly from the positive impulse using:-

$$I^{+} = \tfrac{1}{2}\, td \times Pe \qquad \text{or} \qquad Pe = 2I^{+}/td$$

There is an implied triangular idealisation in the relations above. This effective pressure Pe has been found to be a very effective measure of explosion trace severity and has been found to be the parameter which enables generic response spectra to be derived. It is easily related back to the prototype Biggs formulation.

BIGGS RESPONSE CURVES – THE PROTOTYPE PROBLEM

Derivation of the Biggs curves for peak response

Structural components may be analysed in isolation using the Biggs method, as long as the interaction with the surrounding structure through fixity and the applied loads are negligible or they are represented in the component model.

The Biggs method requires two basic inputs, the resistance-displacement curve and a loading time history. Design charts are available for the calculation of the peak response in terms of ductility values, given the load duration to natural period ratio td/T and the ratio of peak overpressure load to component resistance R/Ppeak or R/Pe. For a triangular load time history Ppeak is equal to Pe.

The method is based on a triangular idealization of the pressure time history. The Response Spectra, generated as part of this work, have avoided the limitations of this assumption by using experimental or simulated time histories generated using the FLACS CFD code.

Under increasing uniform loading, the member deflects elastically up to its effective yield displacement Xe. Further loading results in no increase in the resistance R of the member – it is assumed that the member is deforming purely plastically. If the displacement reduces after plastic deformation then it is assumed that the resistance of the member returns to the pre-plastic (or elastic) form on a line parallel to the line representing the initial elastic deflection.

The Biggs model idealisation was implemented for a range of triangular load durations, natural periods, effective pressures Pe and structural resistances, R. The resulting peak response curves have been re-derived as shown in Figure 4 and checked against published tables.

This chart enables the peak response of the member to be calculated. The vertical axis is in terms of the ductility, which is the number of multiples of the yield displacement the member will reach under the loading.

Response surfaces

Response surfaces have been calculated for a large number of experimental and simulated pressure traces. Each pressure trace was run through the response calculation for 23 natural periods chosen to give td/T ratios in the range 0.1 to 10. The traces were each run for each natural period and for 100 resistance values chosen to give an R/Pe ratio in the general range 0.2 to 2. This yielded a response surface with 2,300 points for each trace.

A typical response surface, for a single idealised triangular load time history is shown in Figure 5. The horizontal axes are the target structure's natural period T and the resistance R. The vertical axis is the peak deflection expressed in terms of ductility for the particular values of T and R for the point considered. (For a triangular load Ppeak in fact is equal to Pe.)

The contours on the response surface correspond to ductilities of 1, 10 and 100. This response surface is an alternative representation of the Biggs' curves. Vertical sections parallel to the natural period axis are the conventional Biggs curves for fixed R/Pe values as shown in Figure 4.

The contours on the surface represent the values of natural period and resistance which give rise to the required ductility levels. These contours are the Response Spectra.

Response spectra

Unlike the Biggs response curves, the response spectra are obtained from the Biggs response surface by taking **horizontal** sections at allowable ductility values as shown in Figure 6. Here μ or 'Mu' is the allowable ductility, R/Pe is the required static resistance to effective pressure ratio, td/T is the load duration natural period ratio. The horizontal sections correspond to the contours on the response surface and relate resistance to natural period for fixed values of the ductility.

It can be seen that the curves can be bounded for a large range of natural periods and so a required resistance may often be obtained without precise knowledge of the structure's natural period or load duration. It can also be seen that the required resistance decreases as the allowable ductility increases. The design or assessment may then proceed with this required static resistance, which may be re-interpreted as an equivalent static load.

Note the vertical axis is now **not logarithmic** indicating the insensitivity of the required resistance to variations in allowed ductility and natural period. The R/Pe ratio for the elastic case (μ= 1) varies from 1.57 at the resonant peak to 1 on the right. The portion of the curve to the left of resonance corresponds to the impulsive part of the dynamic amplification factor curve. For higher ductilities the variation to the right is confined to a band of less than 0.2 in width.

R/Pe represents the dynamic load factor applied to the effective peak pressure Pe for a given td/T ratio. This dynamic load factor 'DLF' gives rise to an equivalent static pressure Pstat defined by:-

Pstat = R = Pe x DLF

The triangular pulse has (Fourier) frequency components at td/T = 1, 3, 5…….∞. These discrete frequency components give rise to minor peaks in the response spectrum at these points. Illustrating the principle that the frequency components of the load will give rise to peaks of response at the corresponding points on the response spectrum.

These peaks are a direct result of the triangular idealisation used in the construction of the Biggs curves and have no other physical significance.

LOAD AND RESPONSE SCALING

The characteristics used for the definition of the loading intensity in the Biggs approach are td, the load duration and Ppeak (or Pe) the peak pressure of the triangular pressure time history.

The dimensionless parameter td/T is used in many areas of dynamic response relating to dynamic amplification and earthquake response, for example. This enables the range of response to be extended for traces of varying duration td for ranges of natural period T. The equations of motion which form the basis of the response calculations may be non-dimensionalized by using this form of scaling.

In the Biggs formulation the pressure trace has a triangular time history. As has been stated above, for the triangular load time history the peak pressure, 'Ppeak' and the effective pressure ‘Pe’ are identical. **This is not the case for a general experimental pressure trace.**

In the majority of cases the pressure trace has a Pe less than Ppeak as the area under the trace (the impulse) is less than that of a triangular trace with the same peak and duration.

This has given rise to a measure of the departure of the trace from the triangular shape called the shape factor Sf which is defined by:-

Sf = Ppeak/Pe

This factor is generally greater than unity for experimental and simulated pressure traces.

The structural resistance R is scaled by dividing it by Pe. Responses for double the resistance and double the effective peak pressure are identical so long as the td/T ratio is also the same. This non-dimensional scaling of the resistance has also been found to be suitable for experimental and simulated pressure traces.

ASSEMBLY OF THE RESPONSE DATABASE

Each pressure trace was run through the response calculation for 23 natural periods and for 100 resistance values. This yielded a response surface for each trace.

- Phase 2 tests – 27 tests each with about 20 measurement positions giving about 500 traces.
- Phase 2 simulations – 27 simulations. The first 20 traces were run through the response calculations.
- Phase 3A tests – 9 were selected from the 45 tests giving about 180 traces.
- Phase 3A simulations – 9 simulations were selected from the 45 supplied to correspond to the chosen test results.

The construction of these response surfaces involved in excess of 3,000,000 calculations. Four workstations were kept fully occupied for a period of two months to provide these results.

Response surfaces and response spectra were generated for each trace.

The responses R/Pe were then averaged for each test over all the response spectra for each trace and at each point corresponding to a fixed td/T value as follows:-

$$\text{Mean}\left(\frac{R}{Pei}\right) = \frac{1}{n}\sum_{i=1}^{n}\frac{R}{Pei}$$

Pei is the equivalent pressure for the ith trace

The Pe to be used to determine the required static resistance for the averaged response spectrum is **defined** to be the mean Pe over all traces.

The response spectra were then averaged over all the phase 2 tests to give the spectra shown in Figures 7 and 8.

The Standard Deviations and Coefficients of Variation of the R/Pe values were similarly calculated for each test and between all the Phase 2 tests.

DISCUSSION OF THE FEATURES OF RESPONSE SPECTRA

Analytic studies of response have been performed to check the results in various regions of the response surfaces. Good agreement was found with the numerically calculated results. The shape of the response spectra has been theoretically verified.

Typical (Generic) response spectra are shown in figures 7 and 8.

These are the Response Spectra obtained by averaging over all traces and all tests for the Phase 2 experiments at the Spadeadam site and the corresponding simulations.

Each curve corresponds to a different allowable ductility value from 1 to 10.

The horizontal axis represents the variation of the load duration td divided by the target structure’s natural period T. The required static resistance in any case can be read off from the vertical axis as a multiple of Pe the effective peak pressure which itself is defined as the mean Pe for all the traces obtained throughout the compartment for all the tests.

This has little physical meaning for a whole compartment but will be a useful technique when examining the response of a blast wall where a number of traces are available at different parts of the wall.

The left hand side of each response spectrum below td/T = 0.3 corresponds to the impulsive regime [10] where the shape of the pressure trace does not contribute to the peak response, this is related only to the impulse (or a combination of Pe and duration td). In this regime the analytic solution is:-

$$\frac{R}{Pe} = \sqrt{\left(\frac{1}{2\mu - 1}\right)}\frac{\pi t_d}{T}$$

The middle section, between td/T = 0.3 and td/T = 3 is the fully dynamic part of the response spectrum. This region can be represented analytically for μ=1 and for a trace with a dominant frequency component around td following Reference 10. A half sine wave loading is examined in this reference. This has given a way of comparing the numerical response simulations with closed form solutions. This comparison is not included in this paper due to lack of space. The HSE (OTO) report on this work does contain these calculations.

The right hand side where td/T > 3 corresponds to the ‘pseudo static’ part of the response spectrum [11] where the response is determined by the work done by the applied load and the potential energy absorbed at the moment of maximum deflection. In this regime the analytic solution is:-

$$\frac{R}{P_e} = \frac{2\mu}{2\mu - 1}$$

These expressions enable the curves for differing allowable ductilities to be collapsed down to a single curve by response scaling.

The curves for simulations and experimental results will still differ in the middle region where fully dynamic response occurs for the $\mu = 1$ case.

Comparison between simulated and experimental response spectra

The main difference between the experimental and simulated response spectra is due to the inclusion in the experimental loading of high frequency loading components which are the spikes in the pressure traces discussed earlier. These high frequency components tend to stimulate response at small natural periods corresponding to large values of td/T.

This suggests that a valid correction to a simulated response spectrum for the elastic case would be to elevate the values at the right hand side of the spectrum to those near the td/T=1 values. For higher allowable ductility values no such correction is necessary.

A simulated pressure trace, being smooth, will have a predominant frequency content around the period corresponding to the range td to 2 x td. This gives rise to a peak in the response spectrum in the middle region, particularly for the elastic case. The higher allowable ductility curves have this peak suppressed because of the damping introduced by plastic deformation.

CONCLUSIONS

Experimental and simulated explosion pressure traces have been processed and compared, and their underlying structure examined.

A method has been identified which enables the duration and effective pressure to be calculated for irregular experimental and simulated traces.

The shape of the Response Spectra has been found to be almost invariant between traces and between tests with the correct scaling which is compatible with the Biggs results.

Mean Response Spectra have been constructed giving a suggested form for the Generic Response Spectrum.

The common spectral form for experimental and simulated results has been identified and the main differences identified. A correction has been proposed to bring the simulation Response Spectra into line with those to be expected from experimental results for the elastic case. No such correction is necessary for higher allowable ductilities.

The construction of response spectra from response surfaces has been demonstrated.

The response spectrum approach has been described, which differs from the 'nominal overpressure' approach in that the dynamic characteristics and allowable deformations of the target structure are represented

Response Spectra give the required static resistance and the static design explosion load to be used for simplified explosion resistant design and assessment. The careful valuation of the optimum ductility for a particular explosion analysis avoids expensive over-design based on current connection details to be developed with the required plastic deformation requirements.

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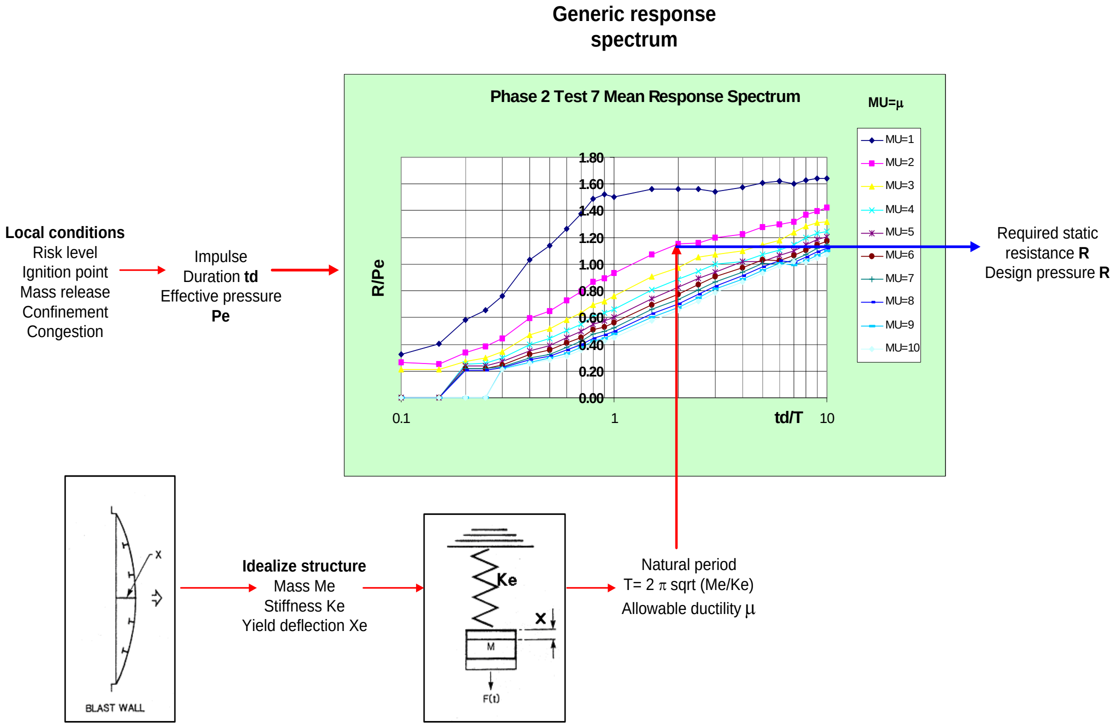

FIGURE 1 THE USE OF RESPONSE SPECTRA TO DETERMINE EQUIVALENT STATIC LOADS

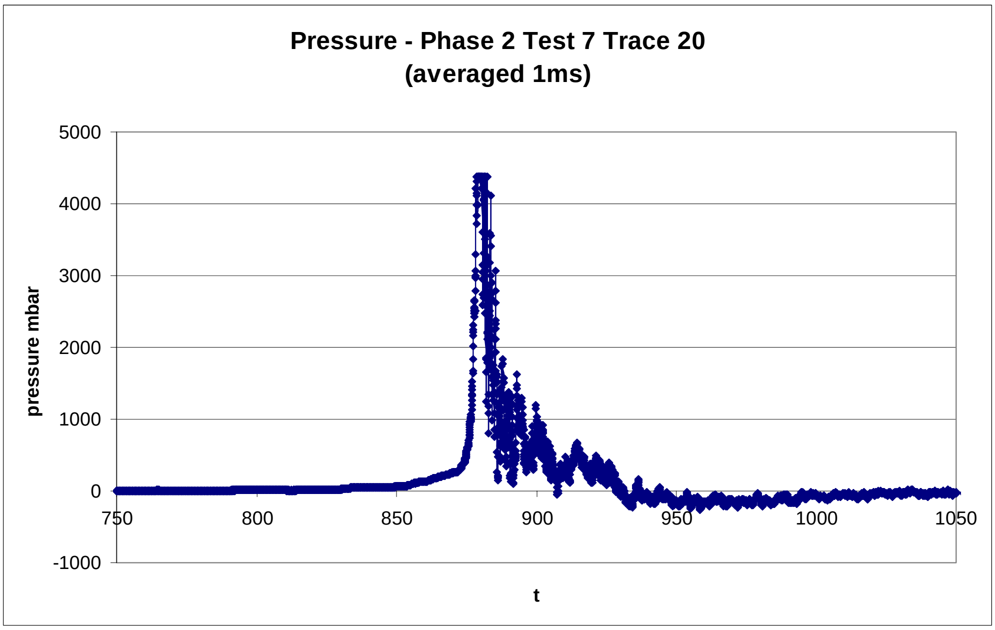

FIGURE 2 TYPICAL PRESSURE TIME HISTORY FROM EXPERIMENT

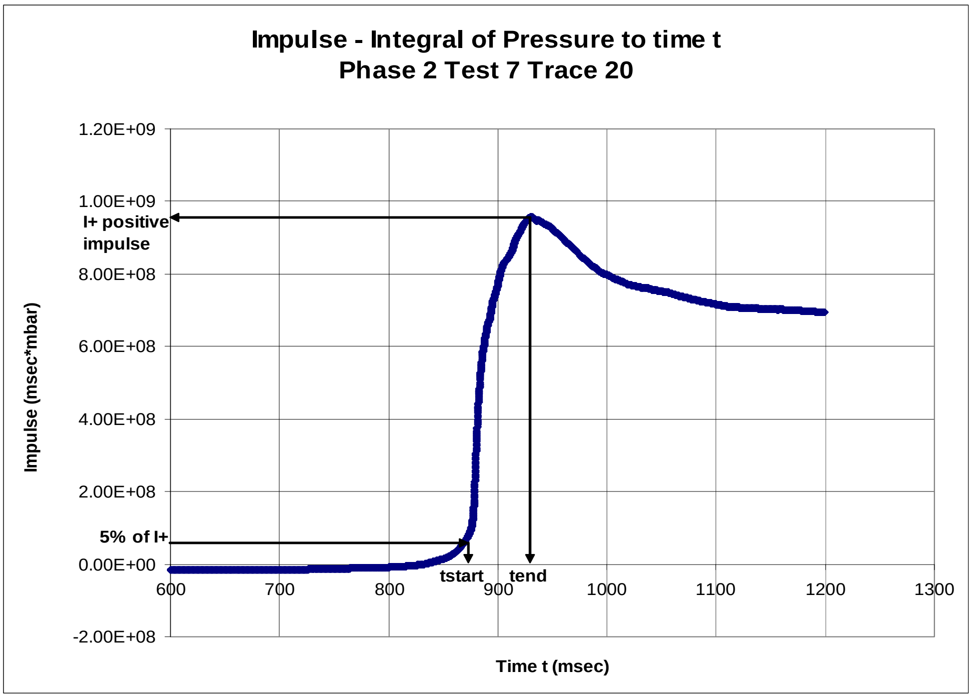

FIGURE 3 METHOD FOR CALCULATION OF DURATION AND POSITIVE IMPULSE FOR AN IRREGULAR PRESSURE TRACE

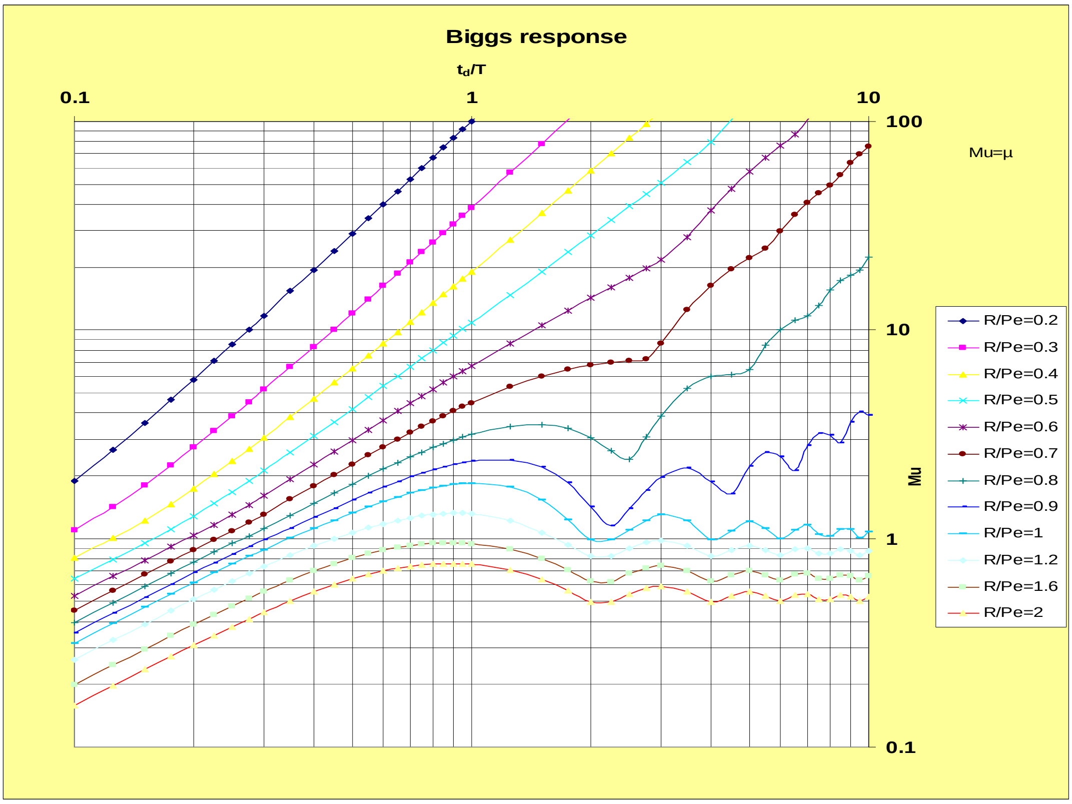

FIGURE 4 BIGGS' DESIGN CHART

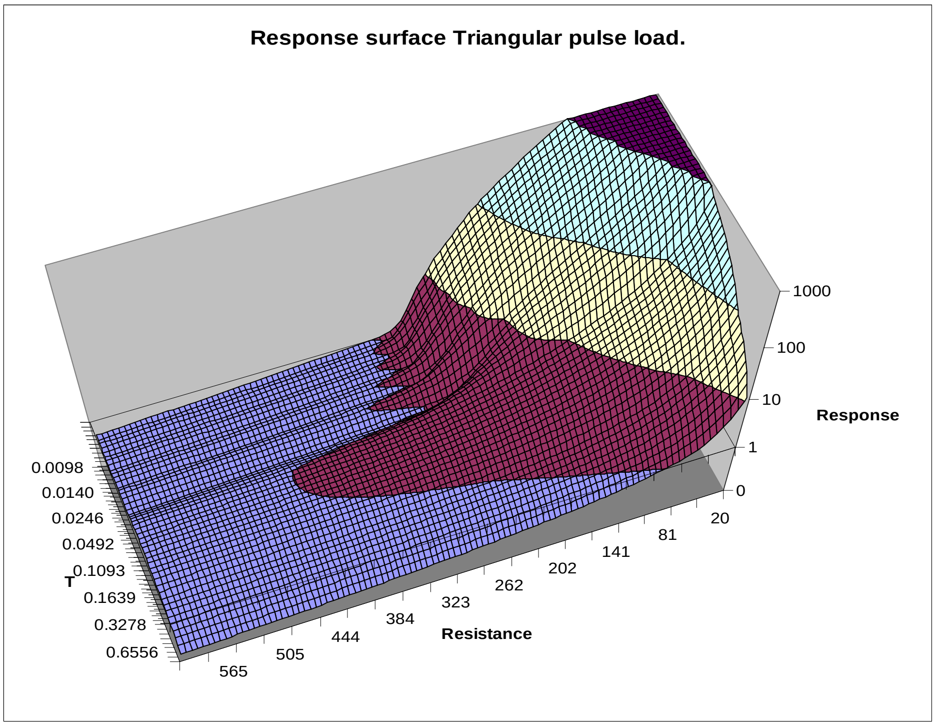

FIGURE 5 RESPONSE SURFACE FOR A TRIANGULAR PRESSURE TIME HISTORY (BIGGS IDEALISATION)

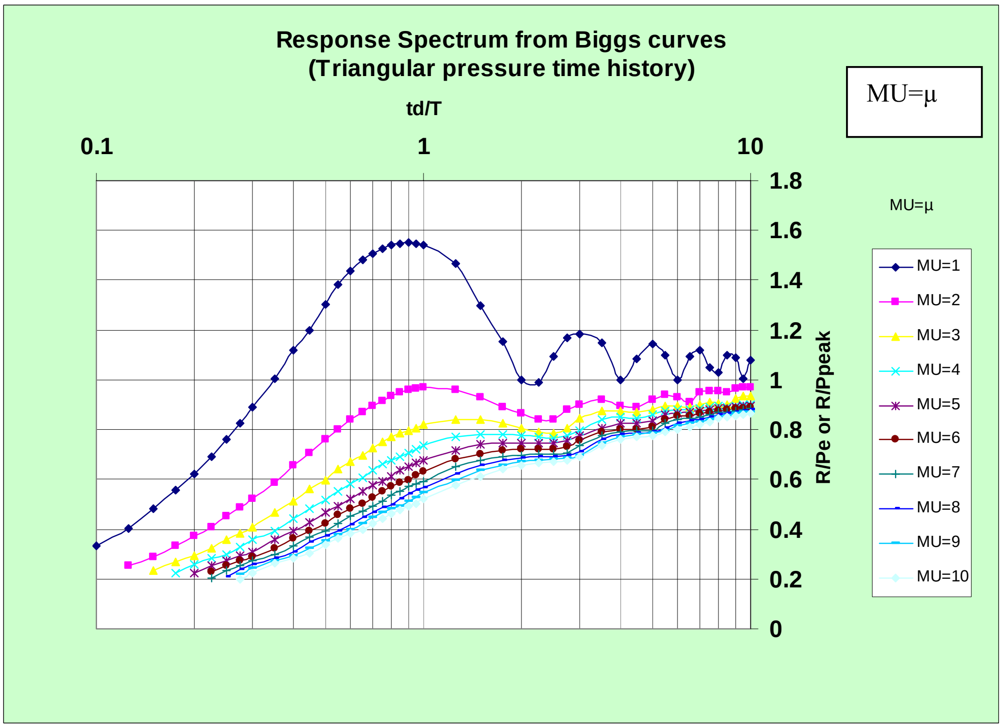

FIGURE 6 RESPONSE SPECTRA RESISTANCE/Pmax VS LOAD DURATION/NATURALPERIOD – BIGGS PROTOTYPE IDEALISATION

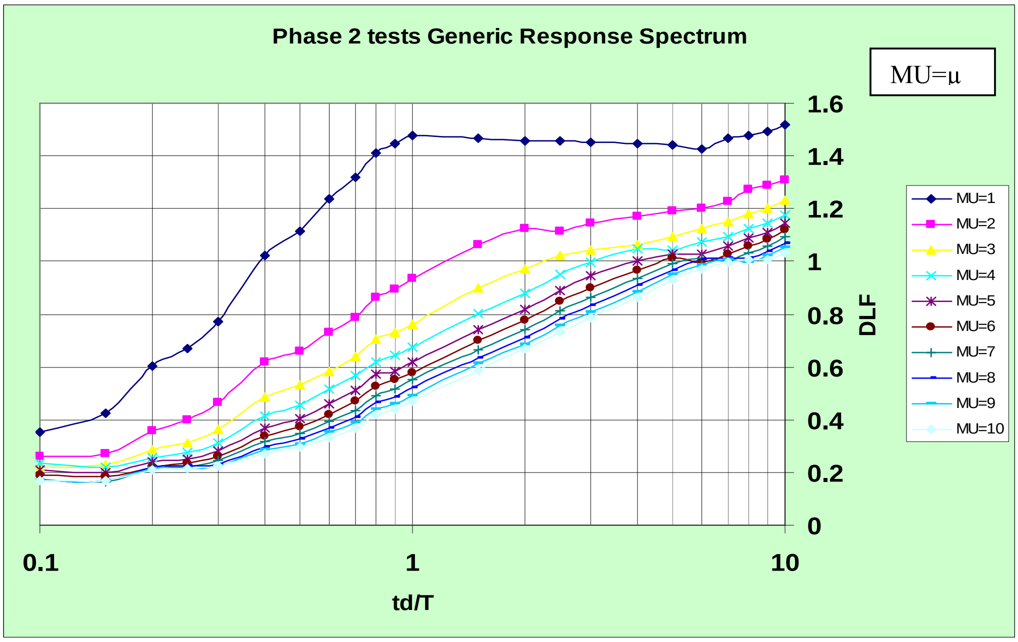

FIGURE 7 MEAN RESPONSE SPECTRUM FOR ALL PHASE 2 TESTS

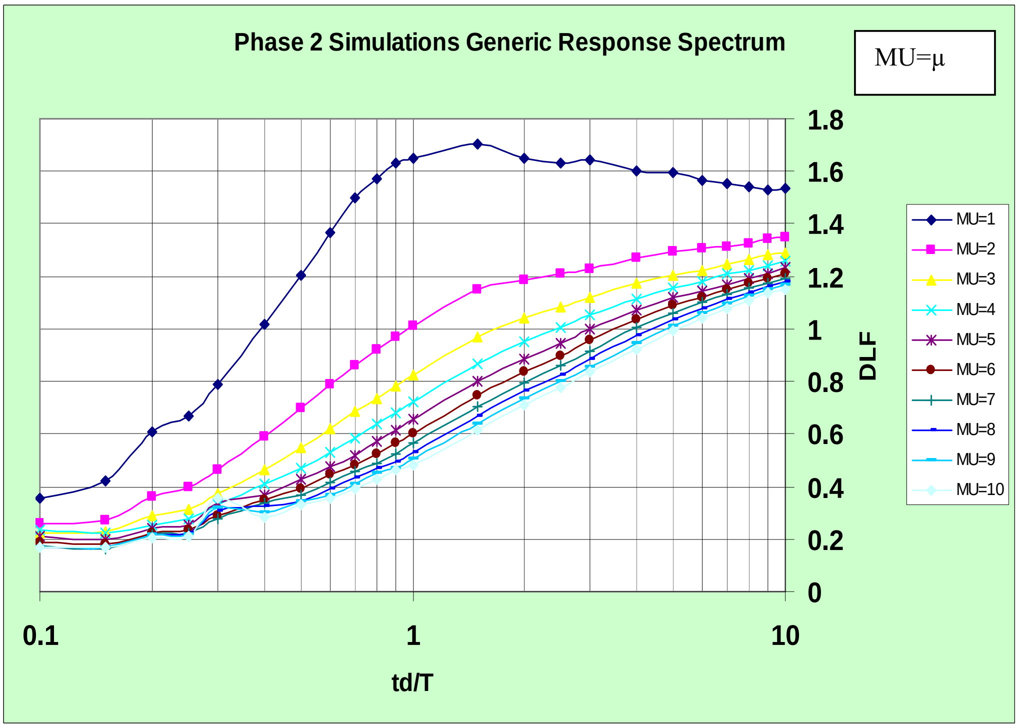

FIGURE 8 MEAN RESPONSE SPECTRUM ALL PHASE 2 FLACS SIMULATIONS