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FORENSIC DETERMINATION OF EXPLOSIVE YIELD FROM MEASUREMENT OF INFRASTRUCTURE DAMAGE

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Abstract: Experts in the field of explosion effects on structures use the severity of damage to infrastructure as a means of estimating the explosive yield from accidental or terrorist explosions. The uncertainty associated with these predictions of explosive yield is likely to be significant but is not normally quantified.

The author has developed a methodology for quantifying the uncertainty associated with the estimation of explosive yield for different types of infrastructure. This methodology uses an engineering model of the component of infrastructure, quantifies the airblast loading, the model parameter errors and the model prediction error and combines this with a Monte Carlo simulation to determine the statistical distribution of explosive yield that caused the observed damage.

Introduction

When an explosion occurs, of unknown magnitude, engineers and scientists are often asked to quantify the explosive yield. They normally calculate explosive yield based on observed damage to infrastructure. Using this calculation of explosive yield, decisions can be taken to mitigate the hazard or threat in the future; however, there is significant uncertainty in estimating the explosive yield based on observed damage. The values reported for explosive yield tend to be best estimates and the associated uncertainty is not normally quantified, which can lead to false confidence in the explosive yield reported. The challenge is to calculate the explosive yield as accurately as possible and to quantify the associated uncertainty to better inform risk-mitigating decisions.

An explosion in an urban environment has the potential to cause many different types of damage, such as: a crater; damage to building facades; damage to street furniture; damage to vehicles; damage to underground utilities; and injuries to people. Some of this damage can be forensically examined to back-calculate the explosive yield. Relatively simple ductile structural systems provide the best estimates for explosive yield. In fact, any structural system where the mass, stiffness and strength can be readily calculated and have been damaged, but not failed, are prime candidates for yield indicators.

There is a large body of information in the public domain that enable the calculation of explosion-induced structural damage. For a specified explosive yield, the airblast loading on a structure can be calculated. The airblast loading can then be used to calculate the damage to the structure. To reverse this process is simply a matter of varying the explosive yield by trial and error until the calculated structural damage matches the observed structural damage. This is the basis of the methodology normally used by engineers and scientists to forensically calculate explosive yield.

If the engineering models are perfect then only a single value of explosive yield could exist that would have created the observed magnitude of damage. If there is any uncertainty in the engineering model then there could be a range of explosive yields that could have created the observed magnitude of damage. In reality the uncertainty associated with yield predictions is significant and must be quantified.

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This paper will describe the methodology developed by AWE to quantify the uncertainty associated with the estimation of explosive yield based on observed damage to infrastructure.

Proposed methodology

Figure 1 shows a flowchart outlining AWE's proposed methodology for calculating the explosive yield distribution based on observed damage to infrastructure.

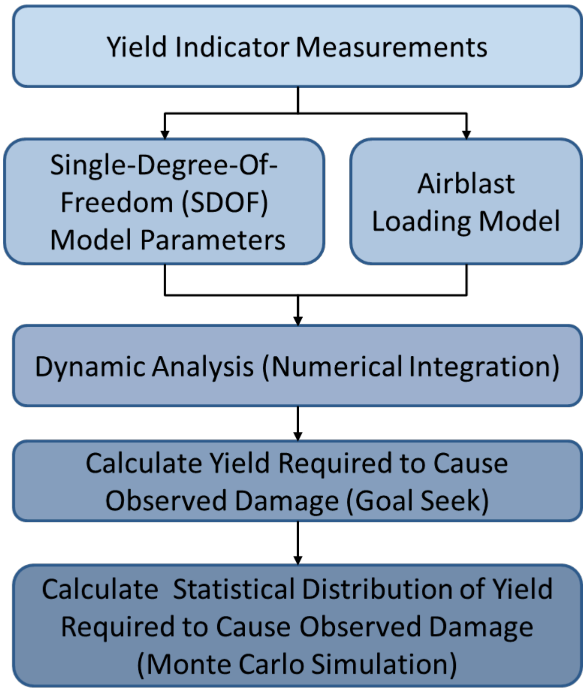

Figure 1. Proposed Methodology for Calculation of Statistical Distribution of Explosive Yield

The first step is to identify and select suitable yield indicators. Yield indicators that have failed will only provide a lower bound estimate of explosive yield. Yield indicators that have not been damaged will only provide an upper bound estimate of explosive yield. The aim is to select yield indicators where the residual deformation can be measured and are located in positions where the airblast loading is not influenced by nearby structures. Nearby structures may cause significant blast wave reflections or shadowing. Typical measurements required include the physical dimensions of the yield indicator, damage and the stand-off distance from ground zero.

The proposed methodology relies on the yield indicator being idealised as a spring-mass system, with the mass travelling in one direction of motion. Such a system is termed a single-degree-of-freedom (SDOF) system. The geometrical and material properties of the yield indicator are used to calculate its strength, stiffness and effective mass (i.e. SDOF parameters). Some of the input parameters for the yield indicator may need to be measured but others can be determined based on suppliers' datasheets or national standards.

An airblast model is required to relate explosive stand-off distance and explosive charge mass to airblast parameters, such as peak incident over-pressure and positive phase impulse. The geometry of the yield indicator is required to determine drag coefficients and the airblast loading function.

Using the SDOF parameters and airblast loading, a dynamic analysis is used to calculate the damage to the yield indicator. The dynamic analysis solves the equation of motion at each time-step and uses numerical integration to calculate the dynamic deflection of the yield indicator.

The explosive yield is varied until the calculated residual deflection of the yield indicator matches the measured damage to the yield indicator.

When uncertainty is introduced to the model then there is a range of possible explosive yields that could have resulted in the observed damage to the yield indicator. A Monte Carlo simulation is used to determine the statistical distribution of explosive yield that could have caused the observed damage to the yield indicator.

This process is repeated for multiple indicators and the statistical distributions of explosive yields for a number of indicators combined to determine the overall confidence in explosive yield.

Sources of error (Twisdale et al (1993))

There are two main sources of uncertainty with any engineering model, model parameter uncertainty and model prediction error. Model parameter uncertainty is associated with the inability to deterministically specify values of the engineering model input parameters. Model prediction error is associated with the inability of an engineering model to perfectly predict the measured effects.

Model parameter uncertainty can have both prediction error and random uncertainty. Model parameter prediction error is generally due to limited data, for example, steel reinforcement quantity. Model parameter random uncertainty is due to inherent variability, for example, material strength. Model parameter errors for all input parameters must be quantified otherwise there will be a false confidence in the yield predictions.

Model prediction error can have both a systematic component (error in the mean prediction) and a random component (variation about the mean prediction). Validation data is essential in order to quantify the model prediction error otherwise there will be a false confidence in the yield predictions.

Example

This example is based on a cantilever steel pole. The properties and SDOF parameters of the pole are shown in Table 1.

Table 1. SDOF parameters

Property	Mean	Standard Deviation
Height	3.0 m	0.1 m
Diameter	42.40 mm	0.14 mm
Wall thickness	2.600 mm	0.087 mm
Dynamic yield strength	486.0 MPa	25.8 MPa
Dynamic ultimate strength	556.0 MPa	27.5 MPa
Young’s modulus	199 GPa	21 GPa
Elastic rotation limit	5.90°	0.74°
Rotational moment of inertia	22.70 kg m^2	2.58 kg m^2
Elastic Moment resistance	9,194 Pa	892 Pa
Stiffness	17,078 Nm/rad	2,050 Nm/rad

The height, diameter and wall thickness of the pole are measured values. Where time permits these values should be measured as accurately as possible to minimise the model parameter prediction errors. If the values are estimated then significant uncertainty may be introduced into the model.

The material properties are not normally measured values. Instead they are based on national or international material standards. The statistical distributions for the yield and ultimate strengths of such steels can be obtained from manufacturers' data. Material strengths are enhanced by appropriate dynamic increase factors (e.g. UFC 3-340-02 (2008)).

The SDOF properties (strength, stiffness and mass) of the cantilever steel pole are calculated using normal engineering methods.

For simple blast environments (environments where the blast wave can propagate relatively unimpeded), airblast parameters are can be readily calculated using the Kingery & Bulmash equations. The airblast loading applied to a structure is a function of the peak pressure and impulse of the incident and dynamic pressures acting in the free-field. Other parameters required to calculate the airblast loading are the presented area of the target and the drag coefficient. The uncertainty associated with the airblast loading can be derived from various papers on this subject (e.g. Bogosian et al, 2002). The distance of the pole from ground zero must be measured in order to calculate the airblast loading.

In this example, the measured damage is the rotation at the base of the cantilever. This should be measured as accurately as possible to minimise the model parameter prediction error.

The cantilever steel pole is idealised as a spring-mass system, as shown in Figure 2.

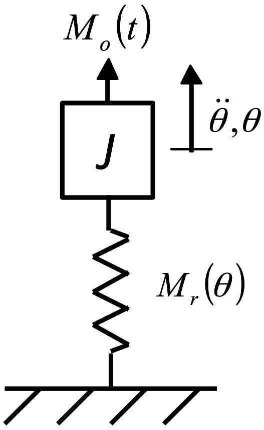

Figure 2. Damped spring-mass system

The dynamic rotation of the idealised system is calculated by solving the equation of motion (Equation 1) at each time-step to calculate the acceleration of the mass. Numerical integration is then used to calculate the dynamic rotation of the system at each time-step. This method is explained in detail in Biggs (1964).

$$\ddot{\theta} = \frac{M_o(t) - M_r(\theta)}{J} \tag{1}$$

Where: $\ddot{\theta}$ = acceleration
$M_o(t)$ = overturning moment
$M_r(t)$ = restoring moment
J = rotational moment of inertia

An example of the resulting dynamic displacements of the cantilever steel pole for various explosive yields is shown in Figure 3. This chart can be used to calculate the residual deflection (damage) to a structure.

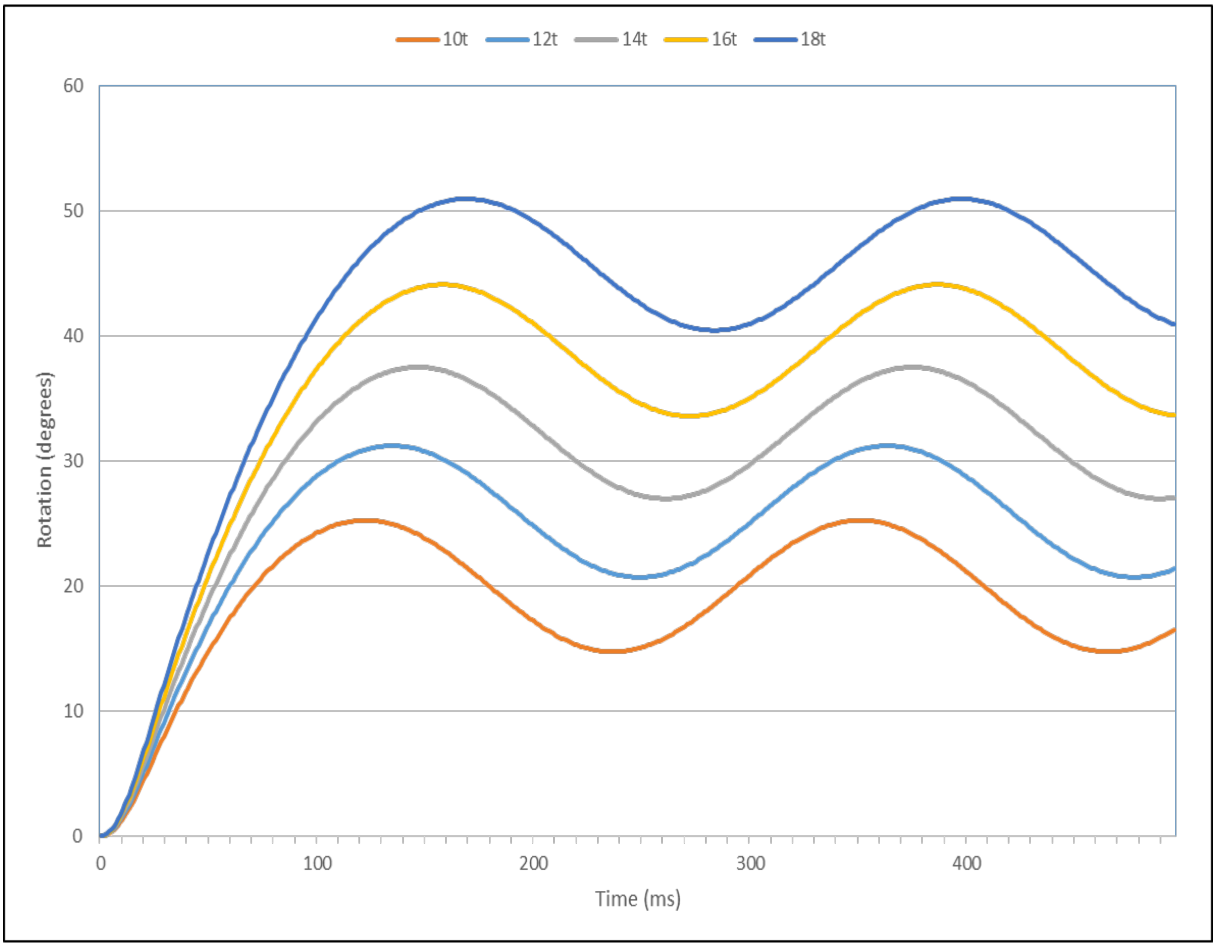

Figure 3. Deflection-time histories for damaged yield indicators

For each iteration of the Monte Carlo simulation, the input parameters are varied in accordance with their probability distribution functions. The explosive yield is varied by trial and error until the calculated residual rotation matches the observed residual rotation of the yield indicator. The explosive yields output from the Monte Carlo simulation can then be grouped into 'bins', such that a graph similar to that shown in Figure 4 can be produced.

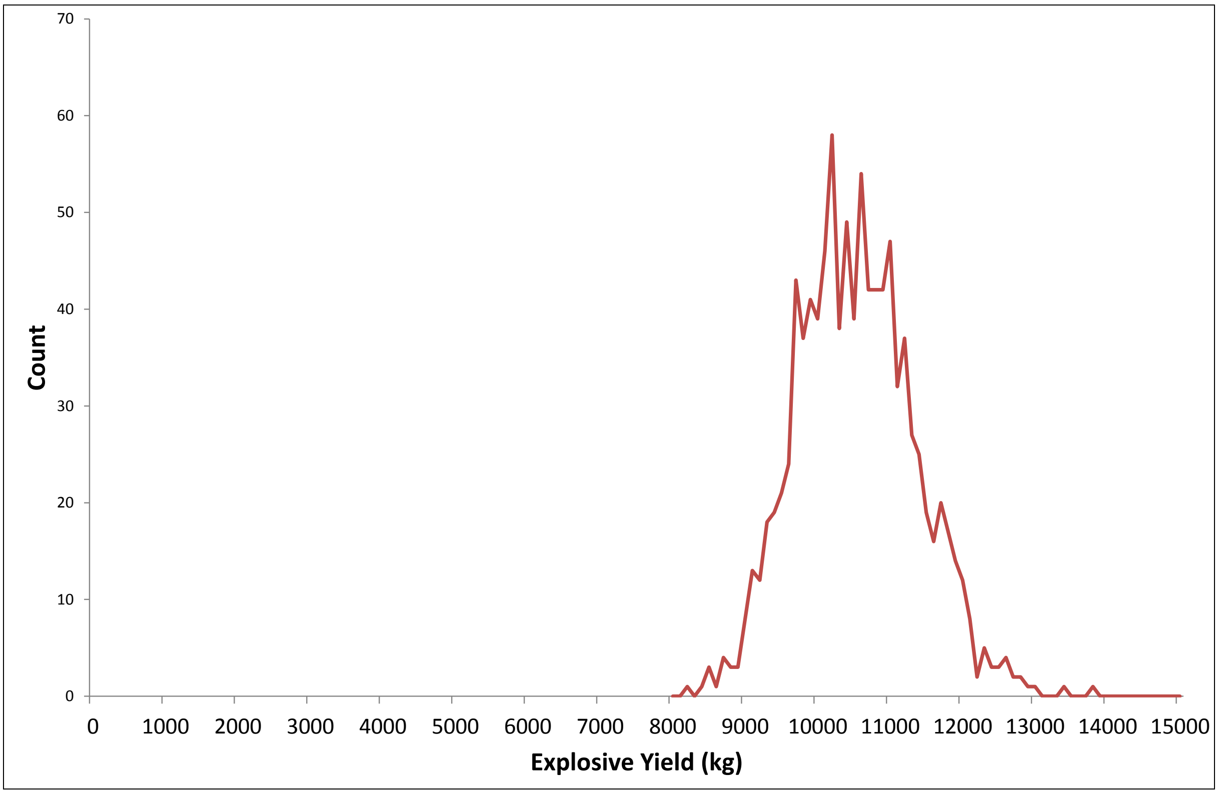

Figure 4. Explosive yield distribution for a single indicator

For multiple explosive yield indicators, the process described above can be repeated. An example of the explosive yield distributions for multiple indicators is shown in Figure 5.

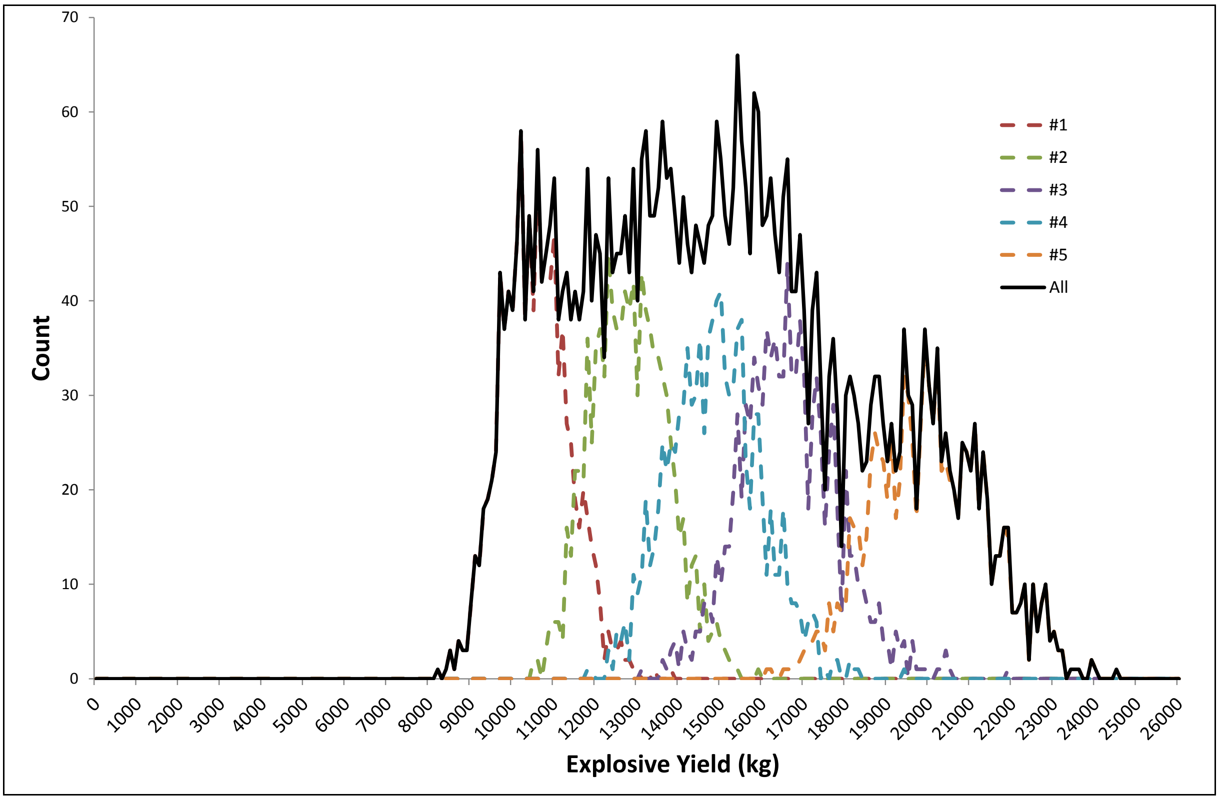

Figure 5. Explosive yield distribution for a multiple indicators

The explosive yield data generated by all indicators can then be expressed as confidence levels. An example of the output is shown in Table 1.

Table 1. Example of explosive yield confidence based on multiple indicators

Probability of Exceedance	**Explosive Yield (kg)**
1%	22,400
5%	20,924
10%	19,918
25%	17,225
50%	14,678
75%	12,102
90%	10,397
95%	9,848
99%	9,162

Discussion

To the best knowledge of the author, this is the first time reliability-based design methods have been used to provide confidence in explosive yield estimations. This represents an improvement on existing methods enabling more informed risk-mitigating decisions.

The example presented in this paper is a very simple example of a cantilever steel pole subjected to airblast loading. The author has used this approach for more complex structural systems, such as buildings. Providing that the structure can be idealised as an SDOF system and the SDOF parameters can be readily calculated then this approach is valid.

All model parameter uncertainties and the model prediction error must be quantified to prevent a false confidence in the explosive yield reported. The model parameter uncertainty should be minimised by accurate measurement, wherever practicable. To minimise the uncertainty in airblast loading, complex blast environments should be avoided. Ideally there should be direct line-of-sight between ground zero and the yield indicator (to avoid the shadowing effect) and no nearby structures (to avoid significant blast wave reflections).

The relative contribution of the model parameter errors and the model prediction error can be calculated to determine which errors provide the greatest contribution to explosive yield error. The most significant errors can be used to determine which parameters need to be measured most accurately or identify where further research may be required.

Conclusion

This paper describes a methodology that AWE has developed to provide an innovative method for quantifying the explosive yield, and associated uncertainty, for different types of infrastructure. This methodology uses an engineering model of the component of infrastructure, quantifies the airblast loading, the model parameter errors and the model prediction error and combines this with a Monte Carlo simulation to determine the statistical distribution of explosive yield that caused the observed damage to infrastructure.

A Microsoft Excel spreadsheet can be requested from the principal author that provides an example application of this methodology.

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