# CORRECTING THE PREDICTIONS BY BAKER-STREHLOW-TANG (BST) MODEL FOR THE GROUND EFFECT

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Simple models representing Vapour Cloud Explosions (VCEs) are widely used in risk assessment for onshore and offshore process installations. Because of their simplicity, blast loads and the risks of a large range of scenarios can be assessed quickly. The Baker-Strehlow-Tang (BST) model belongs to a group of these models using blast curves to predict the consequences of VCEs. The blast curves are usually developed based on modelling results of idealised cases and provide side-on overpressure and impulse or positive duration as a function of distance from the explosion centre. The blast curves developed for BST methodology were based on the predictions of spherical free air explosions and its predictions need to be corrected when applied for explosions near to ground. This paper presents a method to correct the predictions of the BST model and validation of this method.

KEYWORDS: Vapour cloud explosion (VCE), Baker-Strehlow-Tang model (BST), ground effect, blast curves, overpressure and Phast Risk

## INTRODUCTION

The Baker-Strehlow-Tang (BST) model belongs to a group of simple models using blast curves to predict the consequences of VCEs. The other models in this group include TNO Wiekema model (Lees, 1996), TNO Multi-Energy model (TNO, 1997) and the Congestion Area Assessment model (CAM) (Puttock, 1995). The blast curves are usually developed based on modelling results of idealised cases and provide side-on overpressure and impulse or positive duration as a function of distance. The blast curves are then used for assessing the consequences and risks of VCEs. Because of their simplicity, a large range of scenarios can be assessed quickly for QRA.

The Baker-Strehlow model was first published at the 28th Loss Prevention Symposium in 1994 (Baker et al, 1994) This methodology includes a flame speed table, through which the flame speed is decided according to the confinement, congestion and cloud reactivity of the obstructed regions, and a family of blast curves for overpressure and impulse at flame Mach numbers covering deflagration to detonation. Since 1994, the flame speed table had been updated to include a confinement of 2.5D in 1997 (Baker et al., 1997), the blast curves were updated in 1999 and the model was then renamed as Baker-Strehlow-Tang model (Tang et al., 1999), i.e. BST model. A new flame speed table was published in 2005 which gives flame speed relative to a fixed observer, instead of relative to the moving gas as by the original flame speed table, and has excluded 1D confinement (Pierorazio et al., 2005). The BST model used for this study employs the updated flame speed table and blast curves.

The blast curves developed for the BST methodology were based on the predictions of spherical free air explosions. Corrections are required to count for the ground effect for explosions on or near to ground. The current approach is to apply a ground reflection factor to the explosion energy. TNO Yellow Book (1997) suggests the following for the blast effect of vessel ruptures near to the ground. The effective blast wave energy is given by:

$$E_{ex} = A_{sb}E_{av}$$

Where $E_{av}$ is the available energy and $A_{sb}$ is the ground reflection correction factor. In this approach, it is assumed that all available energy will be converted into blast wave energy and the presence of a reflecting ground surface is taken into account through the factor $A_{sb}$. $A_{sb}$ equals one when the vessel is high in the air and two when the vessel is less than 15 degrees above the horizon as seen from the target.

Fitzgerald (2001) used a reflection factor of 2 for ground vapour cloud explosions. Correcting the explosion energy has improved predictions of overpressure away from the explosion source, however, the corrected BST model still under-predicts overpressures of ground VCEs significantly, particularly at the explosion source, as presented in the Fitzgerald paper.

Accurate predictions of peak overpressures of VCEs are often sought after, especially for the design of process installations (Huser, 2009). Simple models, such as BST and Multi-energy models, are particularly useful at the early stage of design because the details required by CFD models are often unavailable. A simple method is presented in this paper to correct the BST predictions for ground effect. The results are validated against measurements and predictions using CFD, the TNO Multi-Energy model and the BST model using the ground reflection correction.

## GROUND CORRECTION METHOD

Factors determining the consequence of a VCE include:

- Fuel type and concentration
- Ignition location and strength

- Confinement and venting
- Congestion, i.e. blockage ratio and obstacle diameters

The GAME project (Eggen, 1998) has derived correlations relating these parameters to the peak overpressures of VCEs for two confinement geometries of low ignition strength. The correlations are:

For no confinement (open, 3D expansion);

$$P_{\max} = 0.84\left(\frac{VBR \cdot L_P}{D}\right)^{2.75} S_L^{2.7} D^{0.7} \tag{1}$$

For confinement between parallel plates (2D expansion);

$$P_{\max} = 3.38\left(\frac{VBR \cdot L_P}{D}\right)^{2.25} S_L^{2.7} D^{0.7} \tag{2}$$

With

| | |
|---|---|
| $VBR$ | volume blockage ratio of the obstructed regions within an explosion source |
| $D$ | characteristic diameter of the obstructed regions |
| $L_p$ | flame path length of the explosion |
| $S_L$ | laminar burning velocity of the flammable cloud |
| $P_{\max}$ | peak overpressure at the explosion source and is used to select blast curves for estimating blast effect. |

The locations of ignition and venting surfaces are not reflected in the correlations directly, but they should be considered in the determination of flame path length for realistic predictions.

Figure 1 illustrates a simple ground VCE and a VCE of the same volume in air. Assuming they have the same congestion, uniform obstacle configuration and an ignition location of the worst-case scenario (i.e. central ignition), the difference in peak overpressure between them is mainly due to the ground effect. Flame path length of the ground explosion would be the radius of the hemisphere

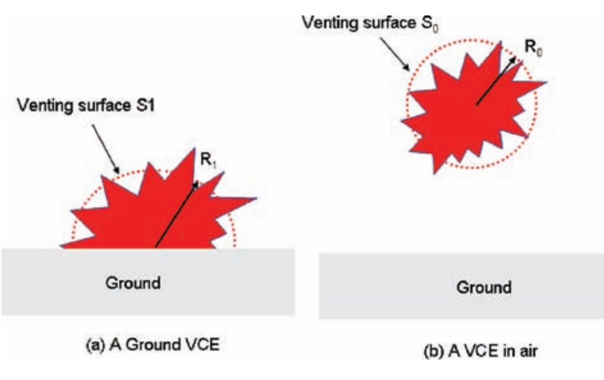


**Figure 1.** Ground and air vapour cloud explosions (VCEs)

given by:

$$R_1 = \left(\frac{3V}{2\pi}\right)^{0.33} = 0.784V^{0.33}$$

Where $V$ is the volume of flammable cloud trapped inside the obstructed regions.

Area of the venting surface (i.e. assuming the flammable cloud may be suitably represented by a hemisphere) is

$$S_1 = 3.86V^{0.66}$$

For the VCE in air, flame path length of the worst-case scenario would be normally radius of the sphere as:

$$R_0 = \left(\frac{3V}{4\pi}\right)^{0.33} = 0.623V^{0.33}$$

Area of the venting surface is

$$S_0 = 4.88V^{0.66}$$

It is clear that the ground VCE has a longer flame path length and a smaller venting surface, and this should lead to a higher peak overpressure at the explosion source.

## CORRECTING THE PEAK OVERPRESSURE AT THE EXPLOSION SOURCE

It is proposed here to correct the peak overpressure for the ground effect, combined with the correction of explosion energy as used by Fitzgerald (2001), and the ground correction factor is related to flame path length and area of the venting surface as.

$$Cf = \left(\frac{R'}{R_0}\right)^{\alpha}\left(\frac{S'}{S_0}\right)^{\beta} \tag{3}$$

With

| | |
|---|---|
| $R'$ | radius of the truncated sphere representing an explosion near to ground as shown in Figure 2 |
| $S'$ | venting area of the truncated sphere representing an explosion |
| $R_0$ | radius of the sphere of equivalent volume to the VCE (as shown in Figure 1) |
| $S_0$ | surface area of the sphere of equivalent volume to the VCE |
| $Cf$ | ground correction factor |

The effect of flame path length on peak overpressure is assumed to be the same as in the GAME correlations. Where $\alpha$ is given a value of 2.75 for 3D confinement and 2.25 for 2D confinement as shown in equations (1) & (2). For 2.5D confinement of the BST methodology, a value of 2.5 is interpolated for $\alpha$.

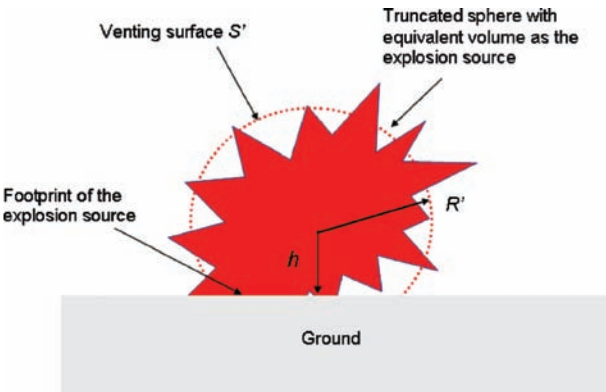


**Figure 2.** An elevated vapour cloud explosion and the representation by a truncated sphere

Obstruction to venting by the ground should have also contributed to the increased peak overpressure of a ground explosion, but it is considered to be less than that of flame path length for VCEs with a degree of confinement of 2D or higher. Also because no data was found to calibrate parameter $\beta$ confidently, the effect of venting surface is ignored here. The ground correction factor is simplified to:

$$Cf = \left(\frac{R'}{R_0}\right)^{\alpha} \tag{4}$$

The ground correction factor by equation (4) depends on both volume and position of the VCE. For a VCE high above the ground, the correction factor is:

$R' = R_0$(i.e. radius of the sphere as shown in Figure1)
$Cf = 1$

This is the case of a free air explosion which had been simulated to derive the BST blast curves and has the minimum correction factor of 1.

For a ground explosion, the correction factor is

$R' = R_1$ (i.e. radius of the hemisphere as shown in Figure1)
$Cf = 1.88$ for 3D confinement
$Cf = 1.77$ for 2.5D confinement
$Cf = 1.68$ for 2D confinement

For an elevated vapour cloud explosion near to the ground as shown in Figure 2, the centre and radius of the representing sphere (maybe truncated) are determined as the follow:

- If the explosion source doesn't touch the ground, the sphere locates at the centre of the explosion source and its radius is adjusted to ensure its volume the same as the explosion source. The sphere would be truncated if its radius is larger than its height $h$.
- If the explosion source touches ground, the height of the truncated sphere is adjusted so that the truncated sphere has the same footprint as the explosion source until it is zero, i.e. the explosion becomes a ground explosion, and the radius is adjusted to enable its volume the same as the explosion source.

CORRECTING THE EXPLOSION ENERGY

The explosion energy is corrected for the ground effect in the same way as done by Fitzgerald (2001). A correction factor of 2 is used for vapour cloud explosions near to or on the ground. This may not be accurate in all cases, but is considered to be conservative.

## IMPLEMENTING THE GROUND CORRECTION METHOD WITHIN THE BST METHODOLOGY

The steps to apply the ground correction method in the BST methodology are:

1. Determine the flame speed using the updated flame speed table (Pierorazio et al, 2005). No ground correction should be applied if the flame Mach number is already the highest Mach number in the table, which is 5.2.
2. Estimate the peak overpressure at the explosion source using the correlation given by Tang and Baker (1999) as

$$\frac{P_{\max} - P_0}{P_0} = \frac{2.4M_f^2}{1 + M_f} \tag{5}$$

3. Estimate a ground correction factor using equation (4) and the correct the peak overpressure obtained from Step 2.
4. Take the corrected peak overpressure into equation (5) and determine the corrected flame speed. The corrected flame Mach number is capped at 5.2.
5. For consequence and risk calculations, the blast curves are selected using the corrected flame speed and explosion energy is corrected using a correction factor given in section 2.2.

## VALIDATING THE METHOD

Predictions using BST model with the proposed ground correction method were validated against measurements and predictions of three models, i.e. BST model with a ground reflection factor of 2, TNO multi-energy model and CFD model AutoReaGas.

TNO Yellow Book (1997) has details of the Multi-energy model and the GAME and GAMES projects have provided guidance on its applications. TNO Multi-energy model has been implemented in Phast Risk v6.60 (a software developed by DNV Software for risk assessment) and it was used to produce the results of Multi-Energy model for this validation. BST model with given ground reflection factors has also been implemented in Phast Risk v6.60 and its results were included. AutoReaGas was used

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**Table 1.** Input data for the multi-energy and BST models for the cases of BFETS3a, EMERGE and Shell Dear Park ethylene explosion (Fitzgerald, 2001)

| | Test setup | | | | | | BST input | | | Multi-energy input |
|---|---|---|---|---|---|---|---|---|---|---|
| Case | Length (m) | Width (m) | Height (m) | Flammable fuel | VBR (%) | Energy (J) | Degree of confinement | Congestion level | Fuel reactivity level | Explosion curve |
| BFETS3a_A (1–4) | 2 | 2 | 2 | Methane | 8.46 | 1.69E + 10 | 2D | High | Low | 6.908 |
| BFETS3a_B (16–17, 19, 22) | 2 | 2 | 2 | Methane | 8.46 | 1.69E + 10 | 2.5D | High | Low | 6.908 |
| BFETS3a_C (24–26, 29, 32) | 4 | 4 | 2 | Methane | 9.62 | 1.69E + 10 | 2.5D | High | Low | 7.452 |
| BFETS3a_D (37–38) | 4 | 4 | 2 | Methane | 9.67 | 1.69E + 10 | 2.5D | High | Low | 7.557 |
| BFETS3a_E (39–44) | 4 | 4 | 2 | Methane | 8.27 | 1.69E + 10 | 2.5D | High | Low | 6.976 |
| EMERGE1 (28–34) | 2 | 2 | 2 | Methane | 10 | 2.49E + 07 | 3D | High | Low | 7.051 |
| EMERGE2 (40–42, 50–) | 2 | 2 | 2 | Propane | 10 | 2.71E + 07 | 3D | High | Medium | 7.577 |
| EMERGE3 (A1,4) | 4 | 4 | 2 | Methane | 10 | 2.03E + 08 | 3D | High | Low | 7.378 |
| EMERGE4 (A2-3) | 4 | 4 | 2 | Propane | 10 | 2.15E + 08 | 3D | High | Medium | 7.904 |
| EMERGE5 (F1, 3, 6–7) | 4 | 4 | 2 | Methane | 4.8 | 2.03E + 08 | 3D | Medium | Low | 4.815 |
| EMERGE6 (F2,4–5) | 4 | 4 | 2 | Propane | 4.8 | 2.15E + 08 | 3D | Medium | Medium | 5.285 |
| EMERGE7 (L1–2) | 8 | 8 | 4 | Methane | 10 | 1.58E + 09 | 3D | High | Low | 8.139 |
| EMERGE8 (L3–4) | 8 | 8 | 4 | Propane | 10 | 1.69E + 09 | 3D | High | Medium | 8.586 |
| Shell Dear Park ethylene explosion | 50.6 | 25.3 | 15.2 | Ethylene with 19% hydrogen | 10 | 1.36E + 11 | 2.5D | High | High | 10 |

**Table 2.** Input data for the multi-energy and BST models for the GAMES test cases

| Parameter | The gas processing case | The chemical plant | The LNG terminal OSR-1 | OSR-2 | OSR 1, 2 & 5 | OSR 1, 3, 6 & 7 |
|---|---|---|---|---|---|---|
| Length (m) | 8.3 | * | * | * | * | * |
| Width (m) | 5.3 | * | * | * | * | * |
| Height (m) | 3.5 | * | * | * | * | * |
| Degree of confinement | 3D | 3D | 3D | 3D | 3D | 3D |
| VBR | 14.0% | 13.0% | 6.0% | 4.0% | 5.1% | 4.8% |
| Congestion level | High | High | Medium | Medium | Medium | Medium |
| Flammable cloud | Propane (4.2%) | Methane | LNG gas | LNG gas | LNG gas | LNG gas |
| Cloud reactivity level | Medium | Low | Low | Low | Low | Low |
| Cloud laminar burning speed (m/s) | 0.52 | 0.45 | 0.45 | 0.45 | 0.45 | 0.45 |
| Typical diameter of all obstacles (m) | 0.25 | 0.55 | 0.48 | 0.46 | 0.47 | 0.48 |
| Flame path length (m) | 4.2 | 15.9 | 12.1 | 8.9 | 14.6 | 15.9 |

*The case consists of multiple obstructed regions and please refer to the GAMES report for details.
**Radius of the equivalent hemisphere and central ignition is assumed.

in the GAMES study (Wercx et al, 1998) and its predictions for the two cases which have no measurements were also used here for validation.

The four sets of test cases used for this validation are:

- BFETS3a. BFETS2 was conducted by the Steel Construction Institute for 1D vapour cloud explosions and BFETS3a was a follow-on project carried out by British Gas in 2000 to investigate gas explosions with the degree of confinement of 2D and 2.5D. Because the new flame speed table is not recommended for 1D explosion, the test results of BFETS2 were not used in this study. Forty-five experiments were performed in BFETS3a and 21 of them were included as in the Fitzgerald study (Fitzgerald, 2001).
- EMERGE. EMERGE tests were carried out by TNO, BG and CMR to investigate the effect of size, fuel reactivity and congestion level on vapour cloud explosion (EMERGE, 1998).
- Shell Dear Park ethylene explosion (Fitzgerald, 2001).
- Test cases of the GAMES project. TNO Multi-energy model was evaluated against measurements of the case of Gas Processing and against AutoReaGas predictions for the other two cases, i.e. the Chemical Plant and the LNG Terminal which have no measurements.

Measurements of the first three sets were used in the Fitzgerald study and the same data were used in this study, Table 1 summarises the input data to the Multi-energy and BST models. Table 2 gives the input data for

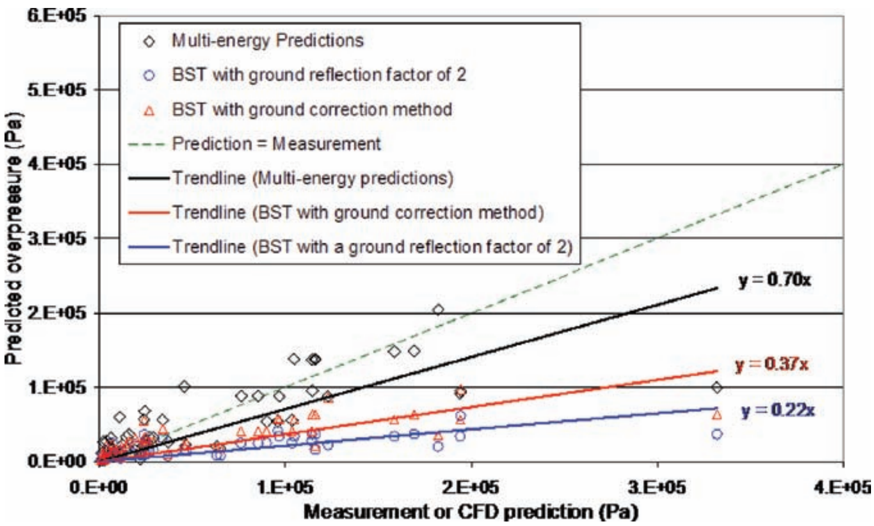


**Figure 3.** Comparing the overpressure predictions of BST and multi-energy models against measurements and CFD predictions (all cases)

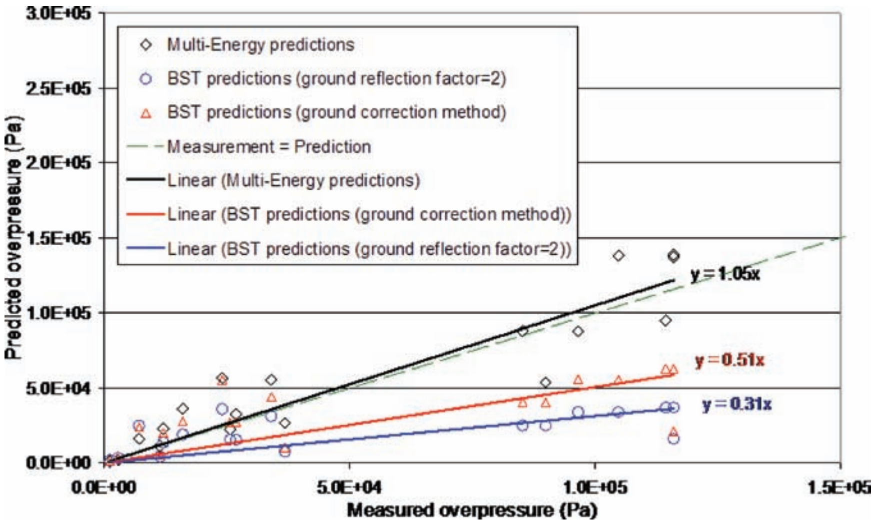


**Figure 4.** Comparing the overpressure predictions of BST and multi-energy models against measurements (selected cases)

the GAMES test cases. The Chemical Plant and the LNG Terminal consist of multiple obstructed regions and their details are not given in this paper and can be found in the GAMES report.

## RESULTS AND DISCUSSIONS

BST model is a simple vapor cloud explosion model using blast curves derived from modeling data of idealized cases and it best suits for VCEs in obstructed regions with obstacles distributed uniformly in all directions. In reality, great variations always exist in obstacle size and distribution. The effectiveness of the model for real scenarios is better evaluated in a wide range of cases. Figure 3 compares the predictions of BST and Multi-energy models against the measurements and CFD predictions of all the test cases listed above. The average errors are −78% and −30% for BST model with a ground reflection factor of 2 and Multi-energy model, and are consistent with the findings by Fitzgerald (2001), which reported an average error of −75% and −23% for BST and Multi-energy model respectively. The small differences between the two studies are due to two reasons: (1) Figure 3 has included the GAMES test cases and has excluded the BFETS2 cases, which are 1D gas explosions and the updated flame speed table is not recommended for them, but were included in the Fitzgerald study; (2) The Fitzgerald study applied an energy efficiency of 20% and 50% for explosions with peak overpressure less than 0.5 bar and 1 bar respectively for the

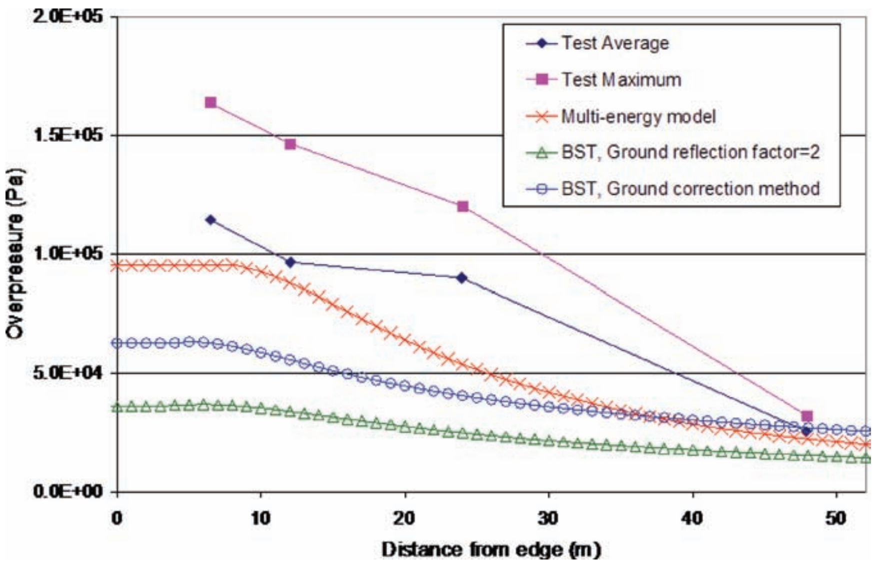


**Figure 5.** Comparing the overpressures along a transect crossing the explosion source (BFETS3a_B)

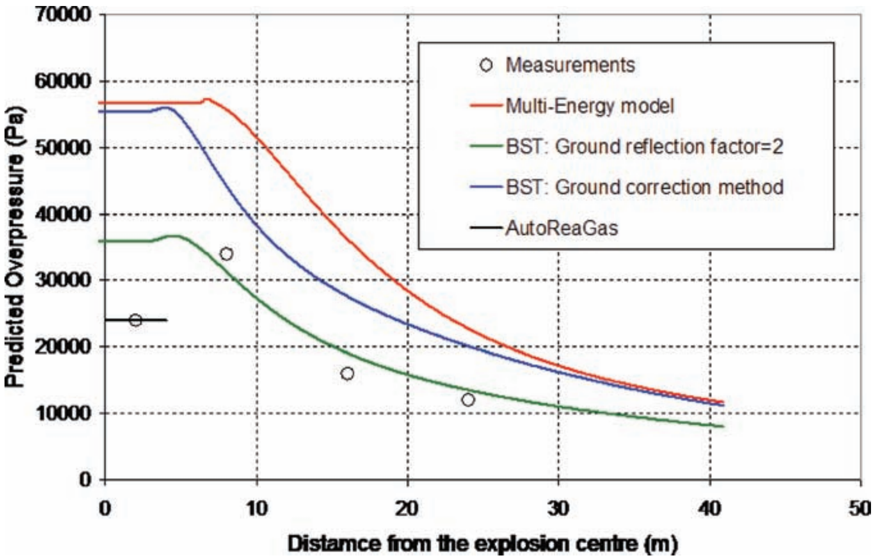


**Figure 6.** Comparing the overpressures along a transect crossing the explosion source (The gas processing case of the GAMES study)

Multi-energy model, and no energy efficiency was applied in this study.

BST model with the ground correction method described above has improved the overpressure predictions. The error of all cases has improved to −63%, as shown in Figure 3, from −78% for the BST model with a ground reflection factor of 2. However, the under-predictions by BST model are still quite significant.

In the Fitzgerald study, the BST model produced better predictions for more realistic scenarios. To reach the conclusion, test cases with small obstructed regions (i.e. EMERGE cases 1–6) and explosions with overpressures higher than 10psi were excluded and only test cases having measurements both in and outside the explosion sources were included. Applying similar selection criteria, Figure 4 shows comparison of the results by BST and Multi-energy models against measurements. Improved predictions are achieved by all models. The error of BST model with the ground correction method has reduced to below −49%, and this is significant better than −69% achieved by BST model with a ground reflection factor of 2.

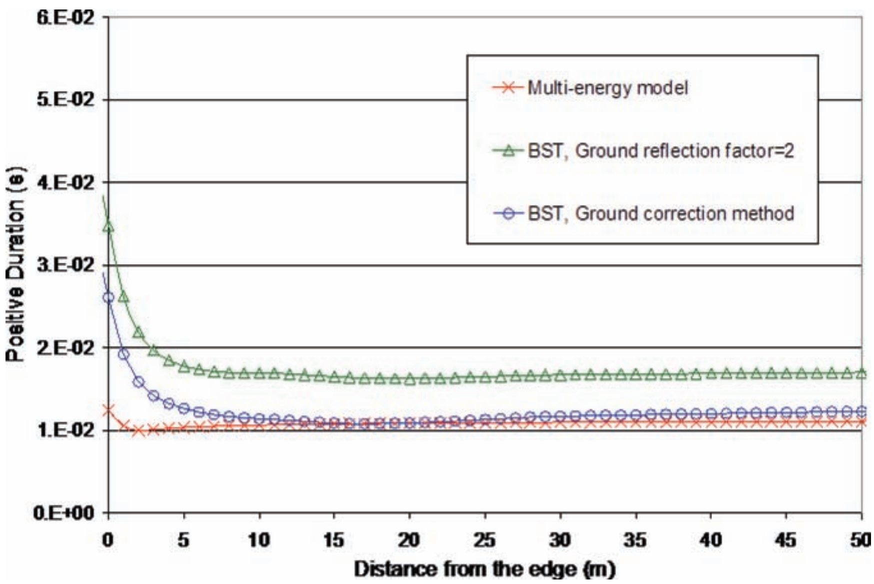


**Figure 7.** Comparing the predicted positive duration along a transect crossing the explosion source (EMERGE6)

Figures 5–6 compares the predicted overpressures against measurements of two selected cases. Figures 5 shows improved predictions of overpressure by the BST model with equation (4) for the ground effect. However Figure 6 shows the results of BST method with a ground reflection factor of 2 in good agreement with the measurements for the Gas Processing case of the GAMES study, the ground correction method has produced conservative predictions at all measurement locations, but less conservative than the Multi-energy model. No measurements were available to validate the predicted positive durations or impulses. Figure 7 compares the predicted positive durations for the EMERGE6 case by BST and Multi-energy models.

## CONCLUSIONS

A correction method has been developed for the Baker-Strehlow-Tang (BST) methodology for the ground effect of vapour cloud explosions. This method is based on the GAME correlations for the Multi-energy model and takes into consideration the change in flame path length for explosions on or near to the ground. Predictions using BST model with this ground correction method have been validated against measurements and predictions of other models for a wide range of test cases.

Improved predictions were achieved using this ground correction method. The error of BST model with the ground correction method have reduced to below −49%, and this is significant better than −69% achieved by BST model with only a ground reflection factor of 2.

In spite of the improved predictions using the presented correction method the predicted results are still significantly below the experimental results.

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