Domino effects between pipelines in pipeline corridors

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In the Netherlands, about 20,000 kilometres of transmission pipelines transporting natural gas, oil products and chemicals have been constructed in the last five decades. New transmission pipelines are now going to be constructed (as much as is feasible) in specially designated pipeline corridors as it become more and more difficult to plan and construct new pipelines efficiently in a country as densely populated as the Netherlands. The width of these corridors, which is normally 70 metres, is such that new pipelines can be constructed and maintained without disturbing adjacent pipelines or cables. However, because of the presence of existing dwellings or of pre-approved plans to build them, the width of some of the corridors is limited to several tens of metres, which is usually insufficient to avoid domino effects occurring between parallel running pipelines. Approximately 100 to 200 kilometres of the corridors are affected in this way. Domino effects in this context are defined as an escalation of the initial effects caused by the failure of a pipeline, resulting in the failure of a second adjacent pipeline with more severe consequences. In cooperation with Dutch pipeline operators and the government, an investigation was started to design domino-free pipeline corridors and to manage the risk in situations where it was thought that domino effects might occur. First, initiating events which could create domino effects were identified, such as overpressure caused by physical explosions, heat radiation resulting from a pool fire or a jet fire, a large temperature drop caused by the release of liquefied gases or supercritical fluids, and earth removal causing free span problems. A range of measures were then investigated that might minimise the possibility of a domino effect occurring. Finally, the incorporation of the domino effect in risk analyses was discussed.

Keywords: domino effects, pipeline corridors

Introduction

In the Netherlands, about 20,000 kilometres of transmission pipelines transporting natural gas, oil products and chemicals have been constructed in the last five decades. As it has become increasingly difficult to plan and construct new pipelines efficiently in a country as densely populated as the Netherlands, new transmission pipelines are now going to be constructed (as much as feasible) in specially designated pipeline corridors (Ministry of Infrastructure and the Environment, 2012). The width of these corridors, which are normally 70 metres wide, is such that new pipelines can be constructed and maintained without disturbing adjacent pipelines or cables. Up to ten pipelines can be accommodated in a pipeline corridor. The risks posed by the pipelines in the corridor are reduced as much as possible (Staatsblad, 2010). Firstly, the likelihood and the consequences of accidents are reduced as much as is reasonably possible by taking measures at the source of risk. For pipelines, the national standard NEN3650 (Nederlands Normalisatie-instituut, 2012) and the Dutch Technical Agreement 3655 (Nederlands Normalisatie-instituut, 2015) are of importance in achieving this goal. The standard NEN3650 specifies the design and construction requirements for steel piping while the Technical Agreement 3655 specifies the risk management system (RMS) to be used for pipeline systems transporting hazardous materials. Secondly, the number of people exposed to the consequences of an accident is limited by adopting a zoning policy. Two measures are used to define this policy: the individual risk (PR) as a measure of the level of protection offered to each individual member of the public, and the societal risk (GR) as a measure of the disaster potential for society as a whole. The individual risk limit is set at 10^{-6} per year for dwellings and vulnerable objects like schools and hospitals. New pipelines should be constructed so that the maximum distance to the individual risk contour of 10^{-6} per year is less than 5 metres (Staatsblad, 2010). For pipeline corridors, the individual risk contour of 10^{-6} per year for each individual pipeline should be situated inside the pipeline corridor (Figure 1).

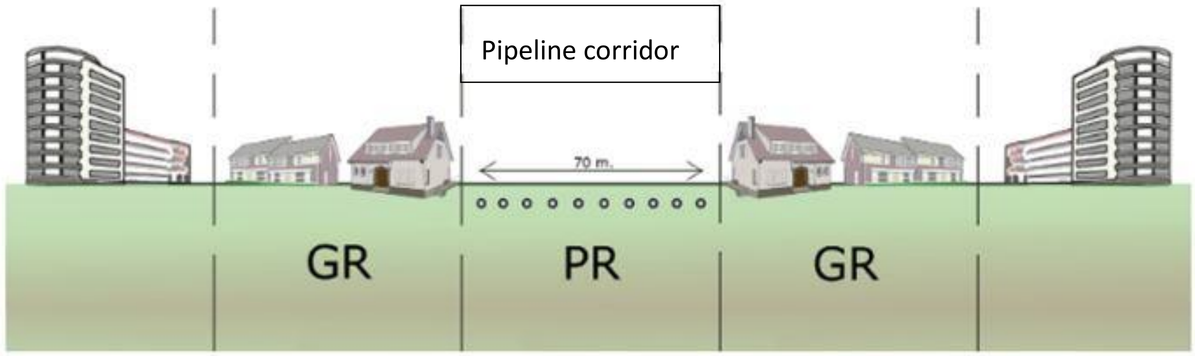

Figure 1 Overview of a pipeline corridor.

Because of the presence of dwellings or of pre-approved plans to build them, the width of some of the designated pipeline corridors is limited to several tens of metres. As the total number of pipelines in a corridor could be as high as ten, the distance between pipelines is reduced to only one to three metres. This distance may be insufficient to rule out domino effects occurring between parallel running pipelines. In total, this applies to approximately 100 to 200 kilometres of the designated corridors, some 5-10% of the total length of the pipeline corridors (Ministry of Infrastructure and the Environment, 2012).

In cooperation with Dutch pipeline operators and the Dutch government, an investigation started to devise a domino-free design of pipeline corridors and manage the risk in situations where it was thought that domino effects could occur. First, initiating events were identified that could create domino effects, such as the overpressure effects caused by physical explosions, the heat radiation effects resulting from a pool fire or a jet fire, the large temperature drops caused by the release of liquefied gases or supercritical fluids, and earth removal causing free span problems. A range of measures were then investigated that might minimise the possibility of a domino effect occurring. Finally, the incorporation of the domino effect in risk analyses was discussed.

This paper describes the investigation made by the working group into the domino effects which occur between parallel pipelines (Werkgroep Domino Buisleidingen, 2016).

Definition of domino effects

Adjacent pipelines may affect each other. For example, the cathodic protection system of one pipeline can be influenced by the cathodic protection system of its neighbour, and excavation activities during the construction and repair of one pipeline can result in damage to another.

The effect of the domino event is often more disastrous than that of the initiating event itself (Cozanni et al. 2005). There are many variations of the definition of a domino effect as the circumstances leading to domino effects can differ considerably (Reniers, 2010). In this study, however, domino effects are defined as an escalation of the initial effects caused by the failure of a pipeline, resulting in the immediate failure of an adjacent target pipeline with more severe consequences ensuing (Figure 2). Initiating events which can result in the failure of the target pipeline are overpressure effects, heat radiation effects, and free span or cooling effects; these are discussed in more detail in the next paragraphs. The failure of a pipeline caused by the release of a corrosive medium from an adjacent pipeline is not considered to be a domino effect, because the second pipeline would not fail immediately as it is expected that there would be enough time to take measures to prevent its failure. Domino effects caused by the failure of wind turbines were not considered in the investigation and are discussed separately (DNV KEMA, 2014).

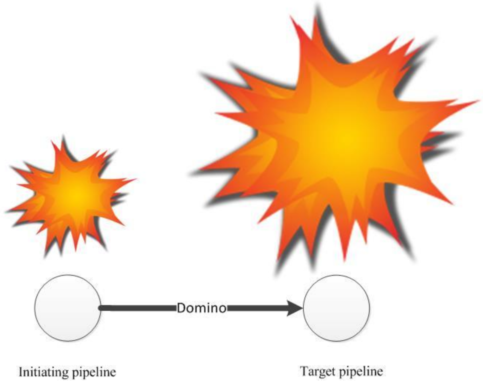

Figure 2 Schematic overview of the domino effect.

.Initiating events which can create domino effects

Depending on the physical state and flammability of the substance transported by the initial failing pipeline, the following initiating events can create a domino effect (Table 1).

Table 1 Initiating events that could potentially can create a domino effect.

Substance	Earth removal	Overpressure	Thermal load	Temperature drop
Flammable gas	Yes	Yes	Yes	No
Non-flammable gas	Yes	Yes	No	No
Flammable liquid	Yes	Yes	Yes	No
Non-flammable liquid	Yes	Yes	No	No
Flammable saturated liquid	Yes	Yes	Yes	Yes
Non-flammable saturated liquid	Yes	Yes	No	Yes

Crater formation

The crater width is an important factor as domino effects between parallel pipelines usually only occur when the domino effect initiating pipeline and the target pipeline are inside the same crater (Silva et al, 2016; Duckworth and Eiber, 2004).

Natural gas pipelines

For pipelines transporting natural gas, crater dimensions depend on the diameter and pressure of the initiating pipeline, the depth of cover and the type of soil covering the pipelines. Several models are available to calculate the dimensions of the crater width as a result of a rupture of a (natural) gas pipeline (TNO, 1973; Leis et al., 2002; Acton et al. 2010; Silva et al. 2016).

Crater widths for several diameter/depth of cover combinations were calculated using the model of Leis (Leis et al. 2002, Acton et al. 2010).

Table 2 Crater width (m) of natural gas pipelines as function of pipeline diameter and depth of cover. Soil type: mixed soil.

	Depth of Cover [m]				
Diameter (mm)	0.8	1	1.2	1.5	1.75
457	4.0	4.6	5.2	6.2	7.0
610	4.4	5.0	5.8	6.6	7.4
914	5.4	6.0	6.6	7.6	8.4
1219	6.4	7.0	7.6	8.6	9.4

The results given in Table 2 imply that a separation distance of 5 metres, equal to half of the maximum calculated crater width, is enough for constructing a domino-free pipeline corridor. However, a recent review of crater formation models indicates that the Leis model underestimates crater dimensions. For a domino-free design of the pipeline corridor, separation distances should, therefore, be up to ten metres (Silva et al. 2016).

Pipelines transporting liquids

For pipelines transporting liquids, the crater dimension depends, amongst other things, on the size of the hole and the hydraulic power of the release. The dimensions can be derived from the method described in NEN 3651 (Mastbergen, 2010; Nederlands Normalisatie-instituut, 2012a) gives crater widths for several pipelines transporting oil products in the event of a full bore rupture. The calculations are ‘worst case scenario’ as the pipeline resistance and pump curve were not taken into account and because conservative values for the operating pressure and capacity of the pump were used.

Table 3 Crater width (m) of pipelines transporting oil products in the event of a full bore rupture.

Diameter (mm)	Crater width (m)
203	26
457	41
610	54
914	58

For a domino-free design of a pipeline corridor containing pipelines transporting oil products, the separation distances between pipelines should be up to 30 metres.

Pipelines transporting saturated liquids

No specific model was found for the calculation of the crater dimension in the event of a failure of the pipeline transporting a saturated liquid although it is believed that the crater dimensions in this scenario would depend on the expansion behaviour of the particular saturated liquid. As no information was found on this subject, the dimensions for both a pure liquid release and for a pure gas release should be calculated and the highest calculated value be taken as the crater dimensions for a release of the saturated liquid (Werkgroep Domino Buisleidingen, 2016).

Physical explosion

The rupture of a high-pressure transmission pipeline results in overpressure effects caused by the physical explosion. Whether an adjacent pipeline fails as a result of the physical explosion depends on the substance transported and on a number of the pipeline parameters of the adjacent target pipeline.

Natural gas pipelines

If a natural gas pipeline ruptures and the target pipeline is also transporting natural gas, the overpressure effects can be calculated by using the TNO model (TNO, 1973). Enhancements of this model have been made in Prophet (Acton et al., 2010). Using Prophet, Tables 4 and 5 give examples of the minimum distances required to prevent domino effects occurring between the domino effect initiating pipeline and the target pipeline. The target pipeline has a diameter of 1219 mm and operates at a pressure of 8 MPa (design factor 0.65) (Table 4) or a diameter of 323 mm and an operating pressure of 4 MPa (Table 5). The overpressure that the target pipeline can withstand is about 7 MPa and 5.5 MPa respectively.

Table 4 Examples of the minimum distances required between natural gas pipelines in order to avoid failure of the target pipeline (1219 mm, 8 MPa) caused by overpressure effects.

Domino effect initiating pipeline		
Diameter (mm)	Pressure (MPa)	Minimum distance (m)
457	8	0.2
610	8	0.3
914	8	0.3
1219	8	0.5

Table 5 Examples of minimum distances required natural gas pipelines in order to avoid failure of the target pipeline (323 mm, 4 MPa) caused by overpressure effects.

Domino effect initiating pipeline		
Diameter (mm)	Pressure (MPa)	Minimum distance (m)
457	6.6	0.2
610	6.6	0.3
914	6.6	0.3
1219	6.6	0.5

Pipelines transporting liquids

If the initiating pipeline is transporting a liquid, the overpressure effects will be marginal as the pressure of the pipeline will drop immediately and minimum distances will be much smaller compared to pipelines transporting natural gas. Therefore no calculations for the derivation of separation distances were performed.

Pipelines transporting saturated liquids

No specific overpressure models were found for pipelines transporting saturated liquids. Based on blast models for vessels (CCPS, 1994) it is believed that the overpressure effects for these pipelines are comparable to those for natural gas pipelines and separation distances of less than 1 metre are assumed to be sufficient. This corresponds with studies on the effect of explosives on underground pipelines where no significant overpressure effects at distances greater than five metres were found (Olarewaju et al. 2010).

Thermal Load

When a failing pipeline transporting a flammable gas or a flammable liquid ignites, a jet fire or a pool fire results. Target pipelines in the same crater as the domino effect initiating pipeline can consequently fail because of the thermal load of the jet fire or pool fire. Whether the target pipeline fails depends on the diameter and pressure of the domino effect initiating pipeline and the cooling potential of the target pipeline. The cooling potential depends on the caloric value of the flammable gas or liquid, the specific heat and thermal conductivity of the product in the target pipeline and the flow velocity in the target pipeline (Acton et al. 2010).

Natural gas pipelines

Table 6 gives some critical flow velocities for natural gas pipelines exposed to the thermal load of an adjacent natural gas pipeline. The design factor of the target pipeline equals 0.65. Under normal operating conditions the gas velocities are high enough to avoid domino effects caused by the thermal load as long as the flow in the target pipeline is maintained.

Table 6: Critical flow velocities (m/s) required to prevent failure of the target pipeline (natural gas/natural gas).

Diameter (mm) of domino effect initiating pipeline, pressure is 8 MPa	Pressure (MPa) of target pipeline		
	4	6.6	8
457	0.45	0.42	0.39
610	0.61	0.56	0.51
914	1.05	0.93	0.81
1219	1.63	1.42	1.22

Pipelines transporting liquids

The cooling potential of pipelines transporting a flammable liquid will usually be larger compared to (natural) gas pipelines. For example, the thermal conductivity of octane is a factor 3.3 larger than that of natural gas (Perry, 2008). In addition, the heat capacity and density of liquids are normally larger than they are for gasses. Therefore, critical flow velocities for pipelines transporting a liquid will be lower compared to gas pipelines, and as a conservative approach, the same critical flow velocities as those for gas pipelines can be used. On the other hand, under normal operating conditions, the velocities of liquids in a pipeline will not be as great as those in gas pipelines and refinement of the assumption may therefore be necessary.

If the initiating pipeline contains a liquid, a pool is formed inside the crater, which causes a pool fire when ignited. As long as the target pipeline is covered by the burning pool, the thermal load will not cause the target pipeline to fail. The volume of liquid in the crater will be reduced as the flammable liquid either burns off or is drained away, but as long as the volume of the liquid flowing from the initially failed pipeline is greater than that of the liquid which is burnt off or drained away, the target pipeline will always be covered by the burning pool. For example, it is estimated that the burning rate of naphtha is in the order of 0.0001 m/s and, for a target pipeline that is initially covered with 0.6 m of liquid, it would take about two hours before the liquid level drops enough to reach the target pipeline (Werkgroep Domino Effecten, 2016). Therefore, a domino effect will not occur immediately after every pipeline failure and there could also be enough time to take measures to prevent a domino effect.

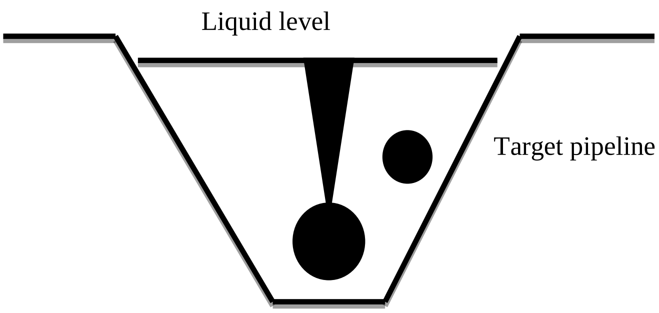

Figure 3 Overview of target pipeline under liquid level of a liquid release.

Low temperature and free span

The rupture of a pipeline transporting a saturated liquid or a supercritical fluid can result in the failure of a target pipeline caused by a large temperature drop. This will only occur when the target pipeline lays inside the pool. Also, if the target pipeline is at free span, after the liquid level in the crater drops below it, the low temperature effects can result in failure of the target pipeline. No generic models for this kind of failure mode were found in the literature. The domino effects caused by low temperature effects and free span should, therefore be investigated specifically.

Measures preventing domino effects

Domino-free design of pipeline corridors

For a domino-free design, the most important measure to take is to exclude the possibility of another pipeline laying in the same crater as the domino effect initiating pipeline. For natural gas pipelines, a separation distance in the order of 10 metres is sufficient to prevent the target pipeline being situated in the same crater (Table 2). For liquid pipelines, separation distances should be up to 30 metres (Table 3).

Preventing domino effects

If a domino-free design of the pipeline corridor is not possible, then the separation distances between pipelines should be such that domino effects caused by overpressure effects, thermal load and free span can be avoided as much as possible.

Minimum separation distance for overpressure effects are given in Tables 4 and 5. The distances are suitable if the domino effect initiating pipeline is a gas pipeline. They are also conservative distances for pipelines transporting a liquid or saturated liquid. The separation distances required are usually less than one metre. To avoid domino effects caused by thermal load, critical flow velocities for gas pipelines are calculated (Table 6). It is concluded, that under normal operating conditions, the flow velocities are sufficient to prevent domino effects caused by thermal load.

Additional measures are required if failure of the target pipeline caused by overpressure effects, thermal load or free span cannot be excluded. As external interference is the most important failure cause for most types of pipelines, additional measures, which reduce the probability of failure caused by external interference can be applied such as increasing the wall thickness of the pipelines and placing a fence at the borders of the pipeline corridor. These measures will not prevent a domino effect but will increase the overall safety level of the pipeline corridor.

The design of the corridor is another measure that can be applied. The soil type used in the pipeline corridor, for example, is of importance as it has a significant influence on the width of the crater. Choosing a soil type that minimizes the width of the crater reduces the probability of the occurrence of a domino effect. Clay type soils are therefore preferable to more sandy types of soils, as the differences in crater widths can be up to a factor of two (Silva et al., 2016). Also, in corridors which currently contain no pipelines or only a few pipeline the probability of escalation can be reduced as much as possible by careful consideration of the sequence of the pipelines, laying, for example, pipelines which would produce the most severe effects at greater depths. This reduces the probability of these pipelines being situated in the same crater as the domino effect initiating pipeline. Also, new pipelines in the pipeline corridor could have a heat resistant coating.

Domino effects in risk analysis

If a domino effect event takes place, the failure frequency of the target pipeline will be greater than it would be in a domino-free situation. In general, a 10% enhancement in the failure frequency is used for inclusion of the domino effect in a quantitative risk analysis (RIVM, 2009; Spoelstra et al., 2015). The contribution of the domino effect is added to the failure frequency of the target pipeline (Eq. 1).

$$F_{\text{target pipeline, overall}} = F_{\text{target pipeline}} + F_{\text{target pipeline}|\text{ initiating pipeline}} \qquad (1)$$

If the domino effect is caused by thermal load, the ignition probability should also be included (Eq. 2).

$$F_{\text{target pipeline, overall}} = F_{\text{target pipeline}} + F_{\text{target pipeline}|\text{ initiating pipeline}} \cdot P_{\text{ignition}} \qquad (2)$$

Failure frequencies and ignition probabilities are prescribed in guidelines for the risk analysis of pipelines (RIVM, 2017; Spoelstra and Laheij, 2012; Laheij et al., 2010). Whether the failure frequency of the target pipeline is influenced by more than 10% depends greatly on the type of pipeline (natural gas, flammable liquid or other chemicals). For natural gas pipelines the failure frequency depends on the diameter, pressure, depth of cover and wall thickness and the criterion of 10% will be first exceeded for pipelines with large diameters (> 762 mm). These pipelines often have a large wall thickness (up to 22 mm) and the depth of cover for these pipelines is usually larger than it is for natural gas pipelines with smaller diameters. The absolute failure frequency is, therefore, relatively low. For flammable liquid pipelines and pipelines transporting chemicals, the failure frequency is almost the same for all diameter/pressure combinations (RIVM, 2017).

Conclusions

In this study, physical models and damage models for quantifying the domino effects which occur between parallel pipelines are identified as much as possible. Crater models and domino consequence models are available for natural gas pipelines, in particular, and, to a great extent for pipelines transporting liquid oil products. The knowledge gaps identified mainly concern models describing the crater size after the release of a saturated liquefied gas and the domino effect consequence models for this kind of release. Also, no generic models were found on the effects of low temperature and failure caused by free span. To ensure a domino-free design, it is necessary to exclude the possibility of another pipeline being situated in the same crater as the domino effect initiating pipeline. For natural gas pipelines, a separation distance in the order of 10 metres is sufficient. However, the soil type used in the pipeline corridor is also of importance. For liquid pipelines, separation distances should be up to 30 metres. If a domino-free design of the pipeline corridor is not possible, separation distances between pipelines should be such that domino effect caused by overpressure effects, thermal load and free span can be avoided as much as possible. The minimum separation distances between parallel pipelines to prevent domino effects caused by overpressure effects are in the order of one metre. This distance has been derived for natural gas pipelines but is also useful as a conservative distance for pipelines transporting liquid oil products. To avoid domino effects caused by a thermal load, critical flow velocities for gas pipelines were determined. It is concluded that, under normal operating conditions, the flow velocities are sufficient to prevent domino effects caused by thermal load. Additional measures may be required if failure of the target pipeline caused by overpressure effects, thermal load or free span is possible.

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