Railway System-Motorway System Interference: Design Applications For AV Line Protection On The Milan-Bologna Section

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SYNOPSIS

The Milan-Bologna section of the High-Speed Railway (AV) line runs beside the A1 Motorway for a considerable way, creating a corridor between the two infrastructures known as the "enclosed area" (AI), with an approximate length of 125 km and a width - measured from the foot of the AV embankment to the foot of the A1 embankment – varying from 6 m (narrow flanking areas) to about 35÷80 m ("non-interference areas", also owing to the height of the A1 and AV embankments).

This situation has made it necessary to develop a specific project ("AV – AI – A1 Safety") in order to solve the safety problems relating to the risk of vehicles running off the motorway and potentially invading the railway line, and not only the vehicles themselves but also their loads, and to the potential hazard for motorway users owing to the new structures foreseen within the dedicated corridor.

The main project interventions, considering the constraints of the enclosed area, consist of:
- Civil works to protect the AV line ("defences"), located in the enclosed and/or railway corridor area, with physical and geometrical features to protect the AV line from invasion, summarily represented by:
  - r. c. walls;
  - earth dunes, whether or not reinforced.

Furthermore, the erection of the various types of "defences", defined as 33 typologies representing the entire flanking section, was influenced by the presence within the enclosed area of parts of structures (e.g. road bridge piers, subway ramps), the crossing of water systems (both crosswise and lengthwise), service roads, areas assigned to subcontractors and many other structures, which in several cases further reduce the already restricted space for erecting the "defences". Besides acting as a constraint for design, the said structures often require adaptation (e.g. raising walls, demolition) to make them compatible with the safety structures.

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INTRODUCTION

To reduce its impact on the environment, the new Milan-Bologna section of the High-Speed Railway (AV) line, its route designed to observe AV geometric, planimetric and altimetric features, runs for some way close to the A1 motorway, creating a corridor between the two infrastructures known as the "enclosed area" (AI), with an approximate length of 125 km and a width - measured from the foot of the AV embankment to the foot of the A1 embankment (4th lane) – varying as follows:

- from 6m to 13m for about 21% of its total length;
- from 13m to 20m for about 22% of its total length;
- from 20m to 80m for about 39% of its total length;
- over 80m for about 18% of its total length.

This situation has made it necessary to develop a project for "AV – AI – A1 Safety" in order to solve the safety problems relating to the risk of vehicles running off the motorway and potentially invading the enclosed area and the railway line, and not only the vehicles themselves but also their loads, and to the potential hazard for motorway users owing to the new structures erected within the dedicated corridor in accordance with regulations in force.

During the early design phase, the necessary data for the study was acquired with the co-operation of *Autostrade per l'Italia* (the company that manages the A1) - who, moreover, asked that the motorway barriers should not be relied on to protect the AV line and that the future construction of the 4th motorway lane in both directions should also be taken into account -, and with Italferr (RFI engineering company, supervising AV projects), who provided the "Safety Criteria Organisation Document for Preliminary Design" as reference in solving road-railway flanking problems.

A study was thus undertaken to identify, through probabilistic analysis, the conditions of potential interference between the A1 and the AV line (possible invasion of the railway line by a vehicle running off the A1), on the basis of accident conditions and road traffic on the A1, and to solving the safety problems, considering 100 years as return time (RT) for design incident event.

Numerical simulation models were consequently developed to study protection works for the AV line in the event of interference with unacceptable return times. Standard safety defences and sections were then defined and were lastly applied to the flanking sections (standard layouts and sections).

The simulations showed that, according to the planimetric-altimetric features of the railway/motorway embankments, a vehicle going off the road could be a hazard for railway traffic up to a distance of about 80 m (maximum range of interference), measured from the foot of the AV embankment to the foot of the A1 embankment (4th lane).

Lastly, in order to limit the landscape impact of the protection structures, eventual methods of mitigating the same were identified for each standard defence structure.

DEFINITION OF FLANKING PROBLEMS

The main hazards associated with the AV – AI – A1 system are substantially three. The first is clearly linked to the possible invasion of all or part of the railway area and even to possible collisions with railway traffic. The second is associated with the possible invasion of the enclosed area, which may contain area maintenance and management personnel and equipment. Lastly, the possibility must be considered of collision with the various A1 structures by vehicles – or their parts - running off the road, according to the usual road regulations.

The occurrence of such risks is associated with a set of variables that largely depends on the reciprocal position of the motorway and railway systems in the flanking area (distance and height of the embankments) and on the characteristics of motorway conditions and infrastructures.

During analysis and verification activities, reference was made to the basic principles of the "Safety Criteria Organisation Document for Preliminary Design", which define a combination of horizontal distances and heights of road and railway embankments, making it possible to establish one of the following conditions:

- no interference: absence of any flanking problems, since the railway line is in a planimetric-altimetric position making invasion by run-away vehicles impossible;
- standard flanking: the railway's planimetric-altimetric position is susceptible to invasion by run-away vehicles and it is possible to erect protection structures inside the enclosed area;
- narrow flanking: the railway's planimetric-altimetric position is susceptible to invasion by run-away vehicles, but the space between the two infrastructures is insufficient for appropriate works to be erected in the AI.

Many are the criteria and aims on which the AV – AI – A1 Safety project is based. Studies have been carried out for the future widening of the motorway from three to four lanes, maximising the intrinsic safety of the AV line independently of A1 protection, limiting as far as possible any interventions on the railway track for protection purposes and, lastly, compatibly with the space available.
On the basis of these criteria and aims, various technical interventions have been defined for the areas flanking the A1, in two successive phases, as follows:

- AV line operation and management of the enclosed area according to its present status, with three lanes in each direction;
- AV line operation and management of the enclosed area according to its future status, with four lanes in each direction.

The ideal arrangement for the AI consists of three different service lanes, each reserved for the operation and maintenance works of the two infrastructures and of the enclosed area itself. In actual fact, the "space available" for erecting the protection elements – in view of the reduced distance between the motorway infrastructure and the railway limit – has been defined by considering the possibility of eliminating the A1 service lane and moving the AI service lane between the protection structure and the motorway embankment. With even narrower spaces, the protection structure cannot be erected in the AI and there will be only one service lane. In such a case, the defence structures will be erected on the railway embankment, either at its foot or at the top.

The definition of AV line protection for a light and a heavy vehicle running off the A1 does not take into account any barrier at the edge of the A1 roadbed and/or any existing or foreseen natural obstacles (hedges, trees, etc.).

The nature and extent of the protection structures is based on both geometric and dynamic considerations, taking into account the physical space available for erecting the various protection structures and for the maintenance lanes. At the same time, the sizing of the works involves several basic parameters, such as the angle at which the vehicle runs off the motorway and the speed at which it is travelling at various distances from the edge of the A1, taking into account the possibility that, under certain conditions, the vehicle may lose contact with the road surface, as well as the conditions and configuration of the road surface itself (downward and upward slopes, ditches, stretches with different rolling resistance values).

In all cases in which the distance between the two infrastructures is less that that of the "no-interference" identified, protection structures will be of different kind and consistency. In order to guarantee AV protection, the following protection structures have been adopted, classified according to their location and function:

- *works located in the enclosed area*
  acting as protection against vehicles running off the motorway and any load carried;
  acting as protection only against vehicles running off the motorway (to be used as required by local situations, guaranteeing protection against the load carried in some other way);

- *works erected on the AV embankment to contain the permanent way*
  acting as protection against vehicles running off the motorway and any load carried;
  acting as protection only against vehicles running off the motorway (to be used when protection from the load carried is guaranteed by the height of the railway embankment itself);
  acting as protection against the load only (to be used together with structures guaranteeing protection against the vehicle only);

- *works erected on the AV embankment not acting to contain the permanent way*
  acting as protection against vehicles running off the motorway and any load carried;
  acting as protection against the load only (to be used together with structures guaranteeing protection against the vehicle only);

The protection structures are of two kinds: the first is associated with earth works, in particular with surmountable earth dunes (slope 2/3), or insurmountable reinforced earth dunes. The second type of defence is r. c. walls, which can be erected in the AI, or as a support for or on top of the AV embankment.

STANDARD SECTIONS

33 standard sections have been definitively identified in applying the various solutions for the installation of a "minimum configuration" of the principal defence structures along the stretch. A description of the standard sections is given below, classified according to the distance between the foot of the railway embankment and the foot of the motorway embankment in its future 4-lane + 4-lane configuration (W4):

Standard Section P (6.60 m<W4<13.64)

The case P is the only one structured in a substantially different manner for the actual 3-lane configuration and future 4-lane configuration of the A1, inasmuch as, lacking available space for widening the AI on an embankment, a supporting wall must be provided when the 4th lane is implemented.

This case features a AV wall (included in the original railway design) – here acting to protect the AV line from vehicles running off the motorway – and the A1 wall for the 4-lane configuration, in order to guarantee sufficient space for at least one service lane in the enclosed area.

The AV wall must, in some cases, be raised beyond the height foreseen in the original design, so as to provide safety both in the 3-lane and 4-lane configurations of the A1 (Figure 1).
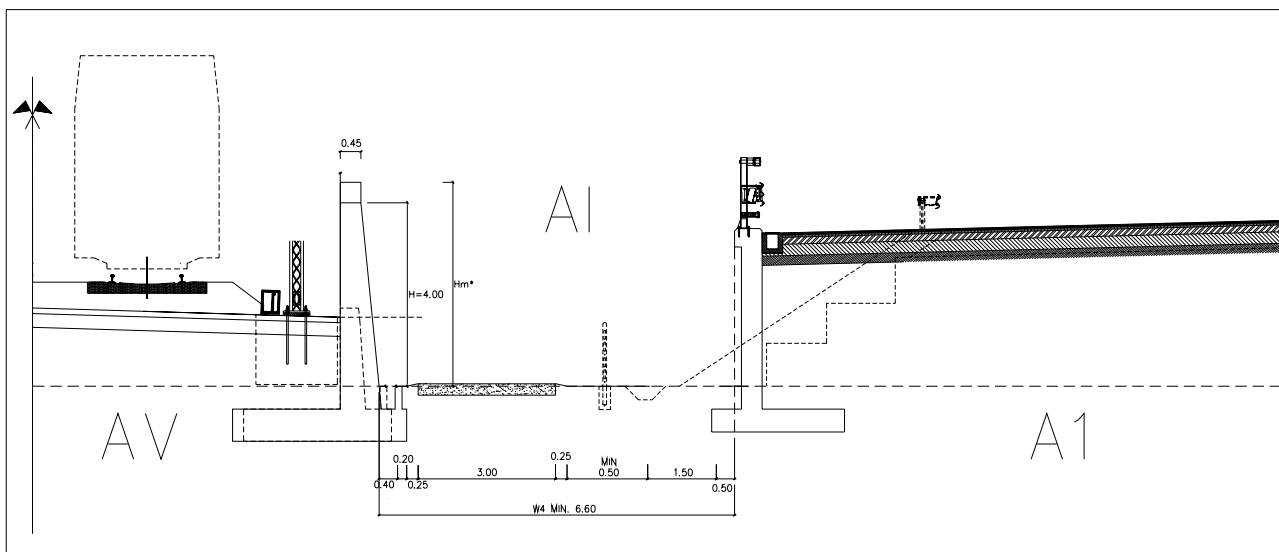

Figure 1 P3 section arrangements

Standard Section N (7.10 m<W4<13.64)

In case N, since the slope of the motorway embankment will be present even in the future 4-lane configuration of the motorway, protection has to be provided against any vehicle (or part of same) running off the road, keeping contact with the slope surface and climbing the AV embankment. In this case, protection does not rely on the height of the A1 embankment, owing to its extreme closeness to the railway embankment.

This case features a AV wall (included in the original railway design) – here acting to protect the AV line from vehicles running off the motorway – and the absence of any A1 wall (Figure 2).

As in case P, the AV wall must in some cases be raised beyond the height foreseen in the original railway design, but for case N the works to be carried out for the 4-lane configuration of the A1 are the same as for the actual 3-lane configuration.
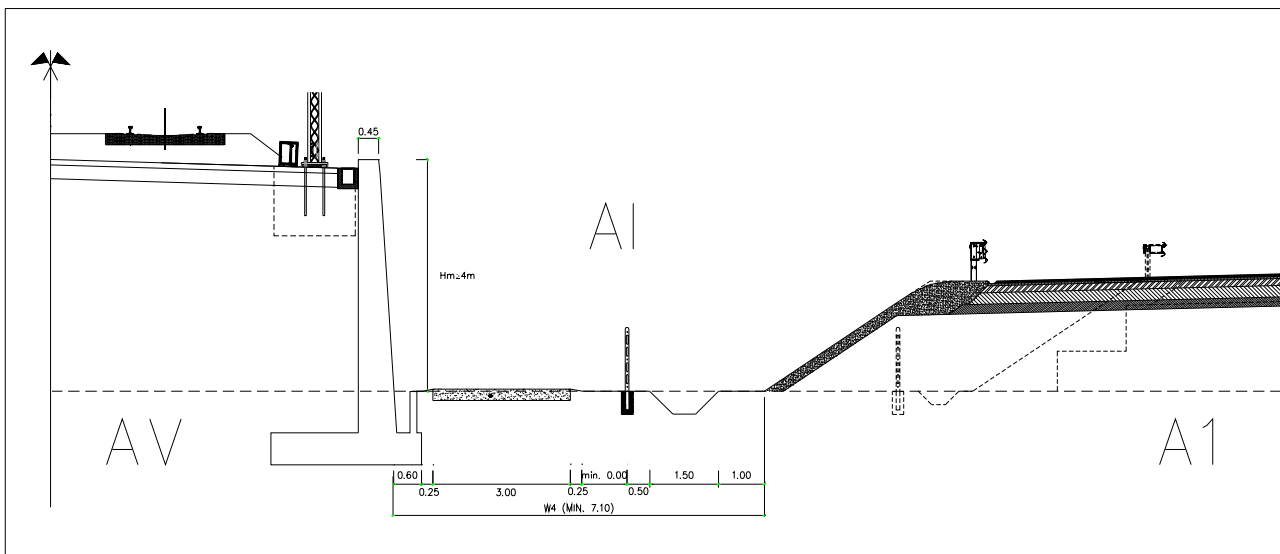

Figure 2 N1 section arrangements

Standard Section M (9.75 m<W4<13.64)

In this case, the space available is sufficient to contain both the railway embankment and the A1 embankment and consequently the original AV design does not include containment works. Owing to the distance between the AV line and the A1, however, safety protection requirements necessitate the erection of wall structures.

As in case N, safety for the AV line can be solved by erecting a AV wall, whose height will depend on the dimensions of the railway embankment.

Alternatively, in order to minimise impact on works whose implementation is already in progress, as well as to avoid substantial design changes, a solution has been identified with a barrier on piles (H=3m) on the edge of the AV embankment, applicable in the case of embankments with a height of more than 1.5m (Figure 3).

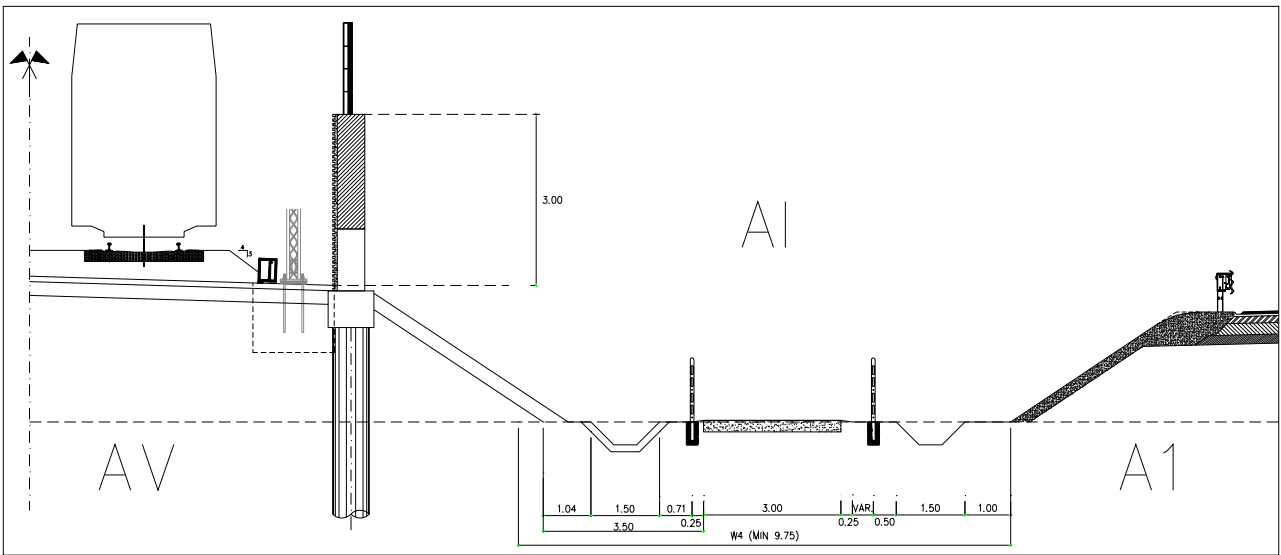**Figure 3 M2 section arrangements**

Standard Section L (12,04 m<W4<20,10 m)

This standard section has sufficient space for two service lanes and lacks any AV/A1 wall.

The safety of the AV line can be assured without intervention on the AV embankment, by erecting a wall (H=3m) between the two infrastructures. On the A1 side, the wall will have a 60° slope for the first 2 metres above ground (Figure 4), thus guaranteeing that it cannot be surmounted by any vehicle running off the road, or by any load carried.
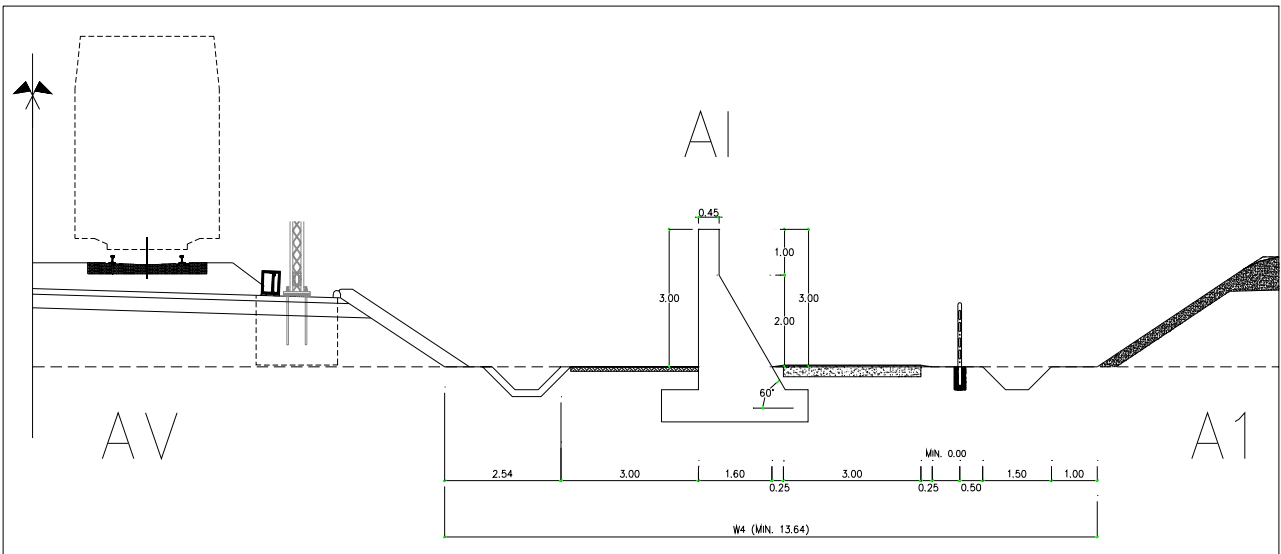

Figure 4 L4 section arrangements

If for any reason the previous defence cannot be utilised, safety from vehicles can be provided by a wall (H=1.90m). Protection from any rolling of the load detached from the vehicle by the collision is guaranteed by the height of the railway embankment, or by erecting a containment wall (H=1.50m) (Figure 5).
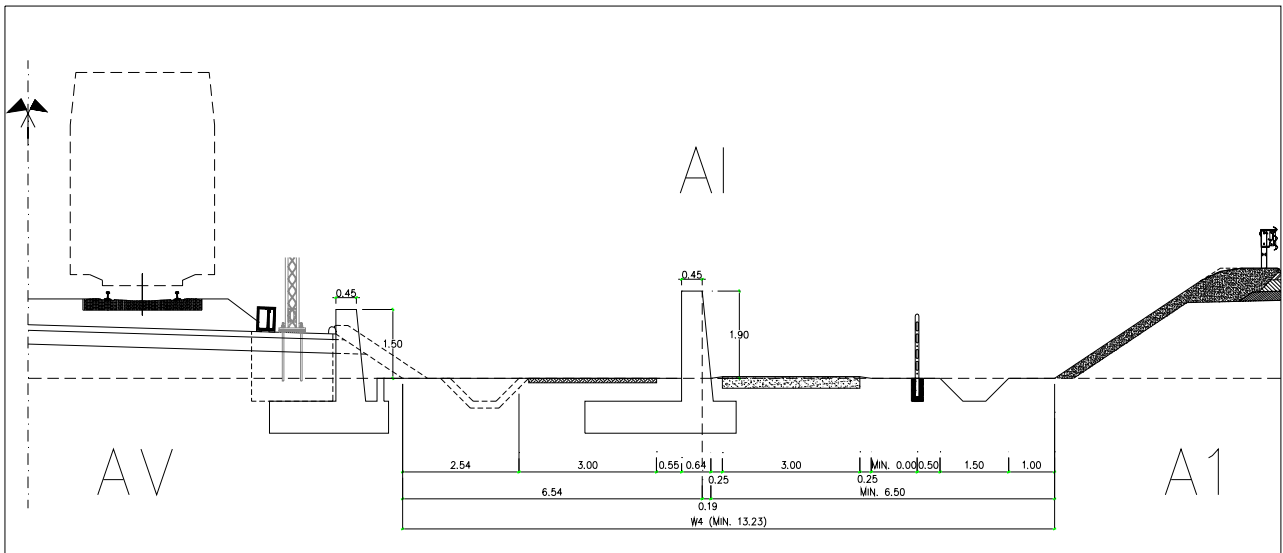
Figure 5 L3 section arrangements

AV safety may be solved by a barrier on piles (H=3m) on the edge of the AV embankment, as in case M, applicable to embankments with a height of Hr>1.5m.

Standard Section I (15,44 m<W4<20,10 m)

This section features three service lanes and no AV/A1 wall. It is similar to standard section L, except that the space available suffices for the third service lane

Standard Section E (15,34 m<W4<22,10 m)

This section features two service lanes and sufficient space for reinforced earth dunes between the two superstructures.

AV safety may be assured by erecting between the two superstructures a reinforced earth dune with a height of H=3m, insurmountable by any vehicle and by any load carried (Figure 6).
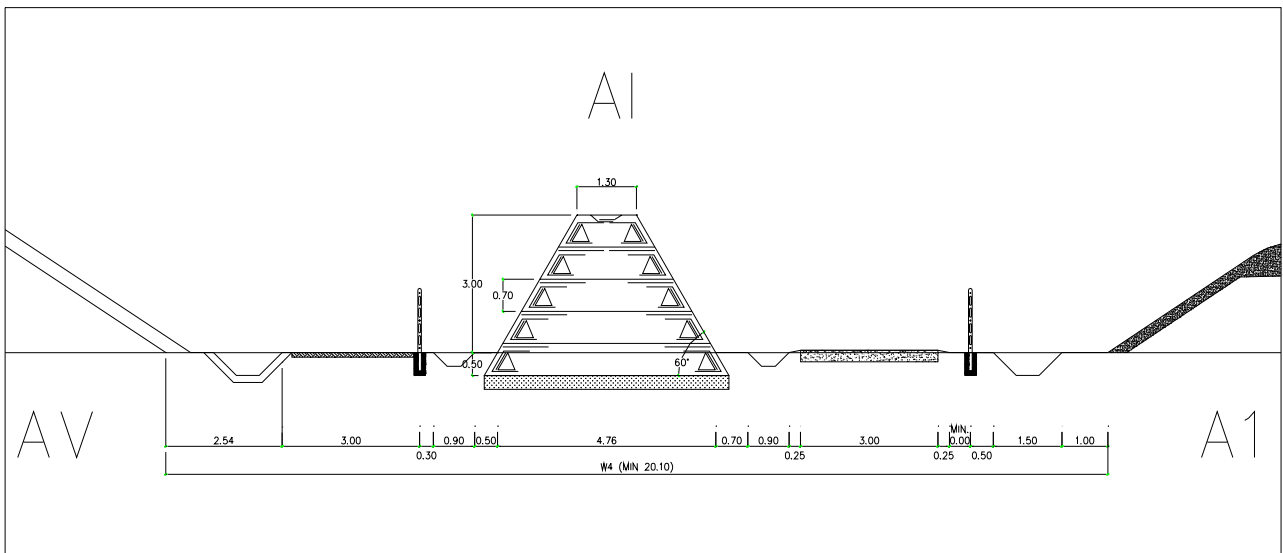

Figure 6 E2 section arrangements

If for any reason the previous defence cannot be utilised, safety from vehicles can be provided by a reinforced earth dune with a height of H=1.90m. Protection from any rolling of the load detached from the vehicle by the collision is guaranteed by the height of the railway embankment, or by erecting a containment wall H=1.50m.

Standard Section C/H (17,34<W4)

This section features three service lanes and sufficient space for a reinforced earth dune between the AV lane and the AI lane or between the AI lane and the A1 lane; it is similar to standard section E, except that the space available suffices for the third service lane.

Standard Section B/F

This section features three service lanes and sufficient space for a surmountable dune with a 2/3 slope, either between the AV lane and the AI lane or between the AI lane and the A1 lane. Its action is to reduce the energy associated with the run-off vehicle, so as to reduce the maximum A1-AV interference distance (Figure 7).
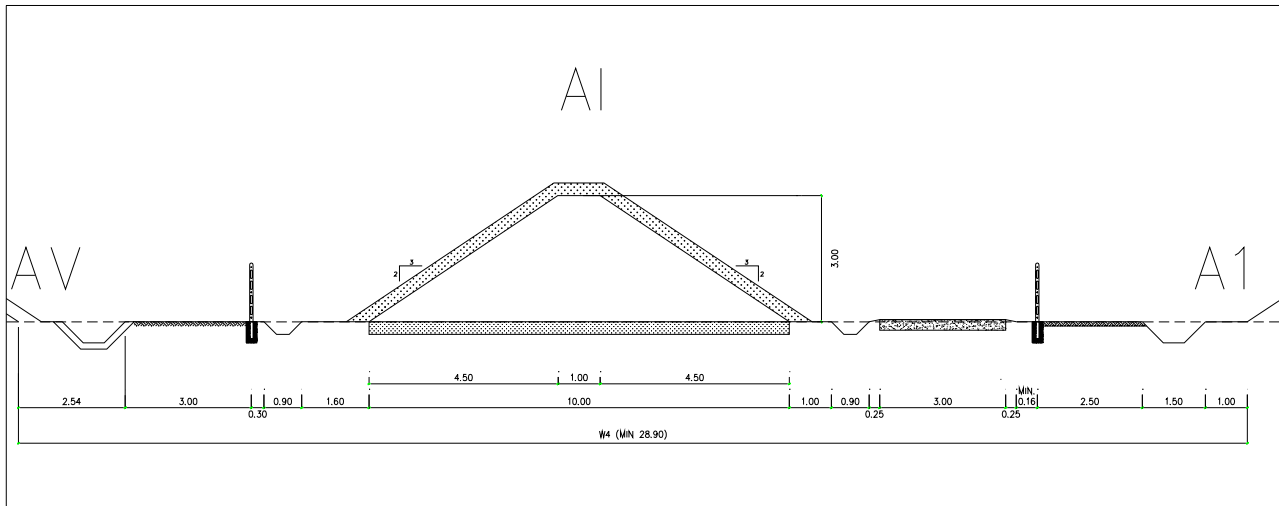

Figure 7 B1 section arrangements

Special Aspects

In general terms, the study does not consider the presence of canals in the AI, since any transversal canals must have a section of at least 23 m to stop any vehicle running off the A1, whereas the diversity in size and shape of the longitudinal canals is such that no generalisation can be made as to their effect (it should be noted that the longest canals are trapezoidal and not very incisive, with limited effect in reducing vehicle run-off distance and consequently with little substantial impact on design choices for railway protection).

To provide continuity to the various works foreseen, the standard sections have, as a rule, been applied without taking into account the presence/location of future parking areas to be implemented together with the 4th lane, envisaging the erection of a future containment wall on the A1 embankment. This arrangement also makes it possible to overlook the precise location of future parking areas.

Where AV line protection is interrupted by ditches or canal/road crossings, or even by changes in protection typology (i.e. gaps), local protection is provided (terminal dunes, wall extensions, etc.). In line with the overall level of protection taken as design basis (return time for critical events leading to the invasion of the AV line = 100 years), interventions have been grouped as follows:

- interventions concerning current AV line protection: in such cases, the gap is an interruption in the protection wall erected on the AV line embankment, and the integrating measure involves continuing protection in the gap area, leaving the higher protection value unchanged.
- self-protected gaps: the geometric dimensions of the gap, defined as its total length plus the dimensions of the terminal protection on either side (also by staggering the same), are insufficient to give access to vehicles.
- non-self-protected gaps: the geometric dimensions of the gap are sufficient to give access to vehicles. In such a case, additional protection is needed on the top or at the foot of the AV embankment, or in the enclosed area, between the current protection and the AV line or between the former and the A1 motorway.
- integrating interventions on the A1 embankment: in some cases, protection will be provided on the A1 (safety barriers at the motorway edge), supplemented by protection in the enclosed area, guaranteeing

protection against vehicles running off the road at an angle of 30° or less, where the total length of the unprotected gap is less than 1% of the neighbouring section.

ADAPTATION OF THE A1 LATERAL SAFETY BARRIERS

Criteria Adopted

Owing to the implementation of the AV line and its safety structures in the AI, A1 border conditions will also change, involving the adaptation of the current barriers at the edge of the motorway in order to limit any consequences to road users of a vehicle running off the road.

Existing 3-Lane Configuration

The current protection structures at the edge of the A1 motorway remain unchanged, except in the cases indicated below. This is valid for all situations, i.e.:
- for sections where there is at present NO lateral barrier to the A1;
- for sections where there is currently a lateral barrier of any class (H2 or H3);
- for all sections where there are retaining walls, walls at foot of slopes or structures, whatever the class of the existing barrier (H2, H3 or H4).

New protection barriers will have to be installed on the A1 (in sections currently lacking any), or the class of existing barriers will be changed in case of one or more of the following situations:
- cases in which a class H2 barrier must be installed: if a vehicle can impact at a speed of over 100 km/h, with a 10-year return time, against the railway embankment or against an earth dune protecting the AV line, with a 2/3 slope; if a vehicle can impact at a speed of over 50 km/h, with a 10-year return time, against an insurmountable reinforced earth dune, with a slope of $\geq 60°$;
- cases in which a class H3 barrier must be installed: when a heavy vehicle can collide against a rigid element (r. c. wall or insurmountable reinforced earth dune, with a slope of $\geq 60°$) protecting the AV line, after going through or over an H2 class barrier (and in any case in all conditions of narrow flanking);
- cases in which the presence of the AV line has made it necessary to erect – on the A1 roadbed – retaining walls, walls at foot of slopes or structures, in which case the structure will be flanked by an H4 class barrier, unless the section is less than 10 m long, in which case the barrier may be class H3.

Future 4-Lane Configuration

For future lateral protection of the A1 with its 4-lane configuration, a class H2 barrier must be erected in the following cases:
- if a vehicle can impact at a speed of over 100 km/h, with a 10-year return time, against the railway embankment or against an earth dune with a 2/3 slope;
- if a vehicle can impact at a speed of over 50 km/h, with a 10-year return time, against an insurmountable dune, with a slope of at least 60°;

On the other hand, class H2 barriers must be upgraded to H3 when there is a possibility of a heavy vehicle colliding against a rigid element (r. c. wall or insurmountable reinforced earth dune, with a slope of $\geq 60°$) protecting the AV line, after going through or over an H2 class barrier (and in any case in all conditions of narrow flanking).

SIZING OF STRUCTURES

The basis for sizing is the maximum force applied perpendicularly to the structure during collision, according to the energy dissipated during the collision.

For an optimisation of the various types of structure to be provided, for calculation purposes the function of protecting against invasion by a whole vehicle running off the road is considered separately from any detachment of the load carried, since the two collision phenomena occur successively and in different ways.

As will be highlighted below, the related tests cannot be carried out according to the consolidated calculation procedures utilised ordinarily in designing the whole Italian railway system. This is because the action considered is absolutely exceptional, not envisaged by current regulations, and because the foreseen protection works have to resist unrepeated loads of short duration, for which the continuing integrity of the structure itself is not as a rule associated with the carrying out of the function for which it is intended.

All calculations for the sizing of protection structures refer to standard situations and the procedures adopted aim at sizing the works on the basis of engineering criteria, which, although not standard, are simple and realistic.

Actions due to collision

The impact force to be employed for sizing purposes equals the equivalent mean and peak static forces during the impact. These values are estimated on the conclusions of three different authors (Hirsch 1978, Bloom 1978, Buth 1978). The first provides considerably lower values than the second and third.

The envelope of the values for these forces (maximum and mean) is represented according to the distance in a straight line and for motorway embankments with a height Hs equal to 0. 2 and 4m (by way of example Figure 8 shows the case for Hs=2m).

In order to find the forces needed for sizing the protection structures, given the distance of the said structure from the right-hand edge of the motorway, a graph must be made using the same, after defining the geometry of the slope, and the values can then be read directly on the ordinates.
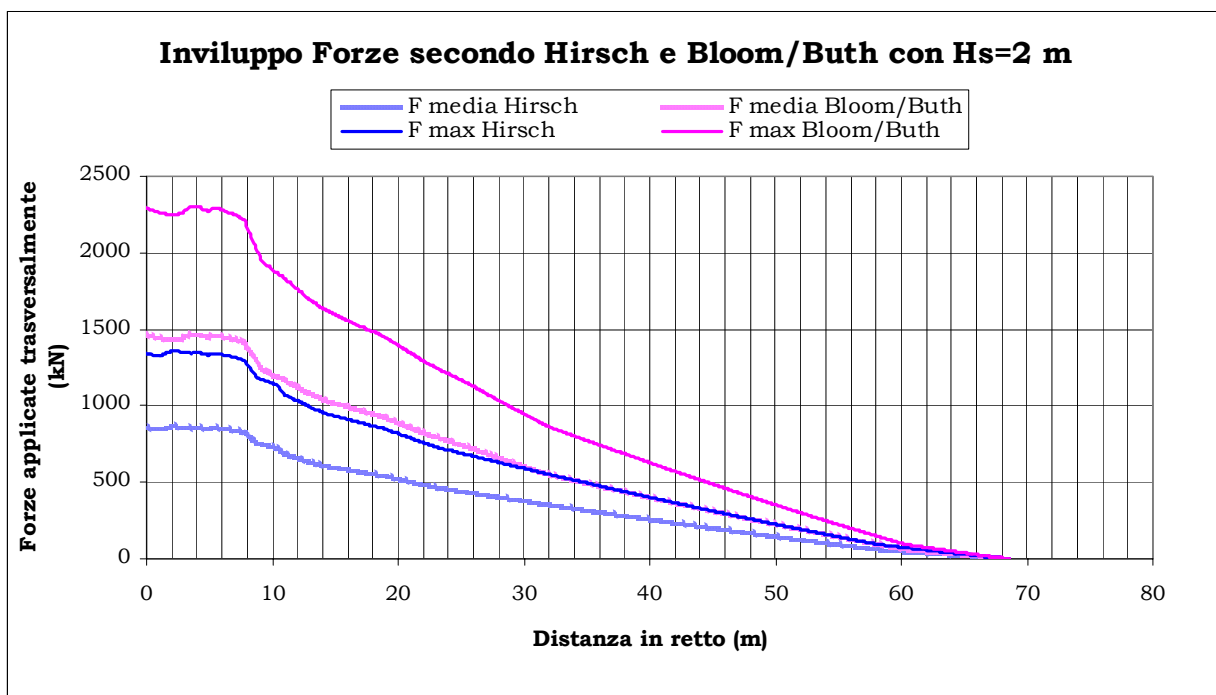

Figure 8 Envelope of maximum & mean forces with Hs=2 m according to the Hirsch study and the Bloom/Buth study

In the case of a "whole" vehicle (tare + load), coming from ground elevation, to collide against a r. c. wall, the transversal force values to be considered for calculation are chosen from among the upper limit of maximum force, focusing particularly on a value at ¾ of the range between the upper extreme (maximum forces estimated according to Bloom and Buth) and the lower limit (maximum forces estimated by Hirsch). It was however decided to adopt a mean value from those provided by the said studies, for the case of collision of the "whole" vehicle with the structure on an upward slope of the railway embankment (protection erected on the AV embankment).

As far as the dunes are concerned, on the other hand, their higher deformable nature was taken into account, assuming the mean value provided by Hirsch.

Similar considerations were taken for the case of the load alone, projected towards the AV line.

In the event of impact by the vehicle with all its load, the highest transversal forces encountered in the most serious standard cases are of 1650 kN for r. c. walls and 700 kN for earth dunes.

REINFORCED EARTH DUNES

Reinforced earth dunes are envisaged in the areas flanking the A1 motorway, and, as a rule, this kind of structure is relied on to protect the AV line in what are considered "normal flanking" areas, where it is possible to avoid building walls, but impossible to erect normal dunes with a 2/3 slope.

Whereas the latter can be surmounted by a vehicle running off the motorway, the aim of the reinforced earth dunes is to provide – owing to their geometry and mass – an insurmountable obstacle in view of the increased slope of their sides. Furthermore, the overall dimensions of the embankment can also be reduced with this kind of work, by exploiting the presence of various kinds of reinforcement.

At present, no significant anti-run-off experiments and applications have been carried out with such structures in Italy. In defining their specifications, reference has consequently been made to similar studies on boulder protection embankments, usually applied over extended areas to intercept, deviate or stop falling stones with high kinetic energy (Paronuzzi 1989, Guasti 1999, Castiglia 2001, Peila 2001, Agostinacchio 2002).

The advantages of such embankments is their minimal maintenance, even after repeated restoration, considerable longevity of the work without any loss in function and an overall uniformity of resistance and behaviour, without any particular discontinuity.

Furthermore, in view of the level and rectilinear morphology of the enclosed area, the impact of this solution is good, since the embankment can be covered with vegetation (compatibly with the slopes required).

Viewed as protection structures, the dunes do not have to remain untouched by impact, but must be intrinsically stable and resist any break-through by a colliding vehicle, the more so, since they are located in the enclosed area at a distance of not less that 6 m from the railway embankment.

Along the Milan-Bologna section, two lines of dunes are currently being experimented near Reggio Emilia (Figure 9 & Figure 10 symmetrical dune with a height of 3m and a slope of 60°; Figure 10 & Figure 11, dune with differentiated slopes (60°/90°) with vertical 3m high faces made of gabions).

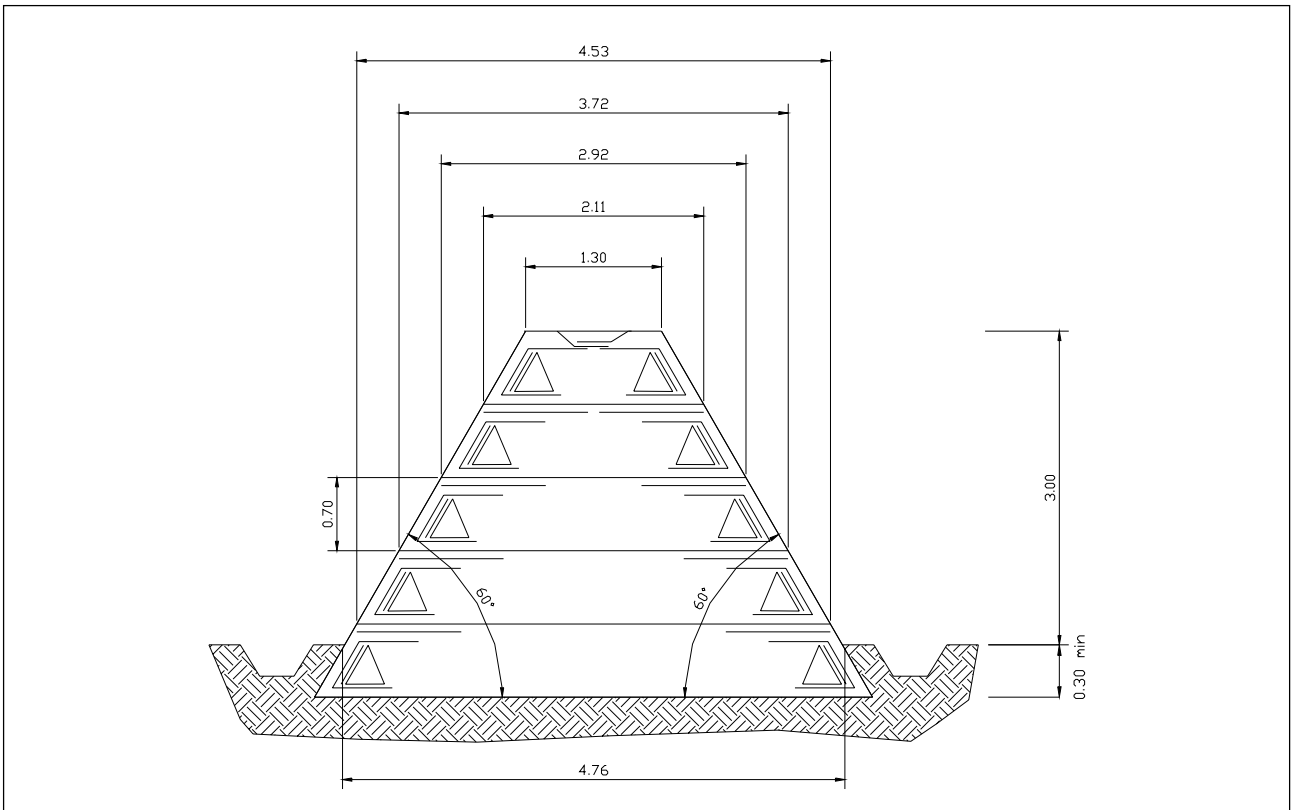**Figure 9 Symmetrical dune arrangement with slopes of 60°**

Figure 10 Photo showing the implementation of a symmetrical test dune with a 60° slope
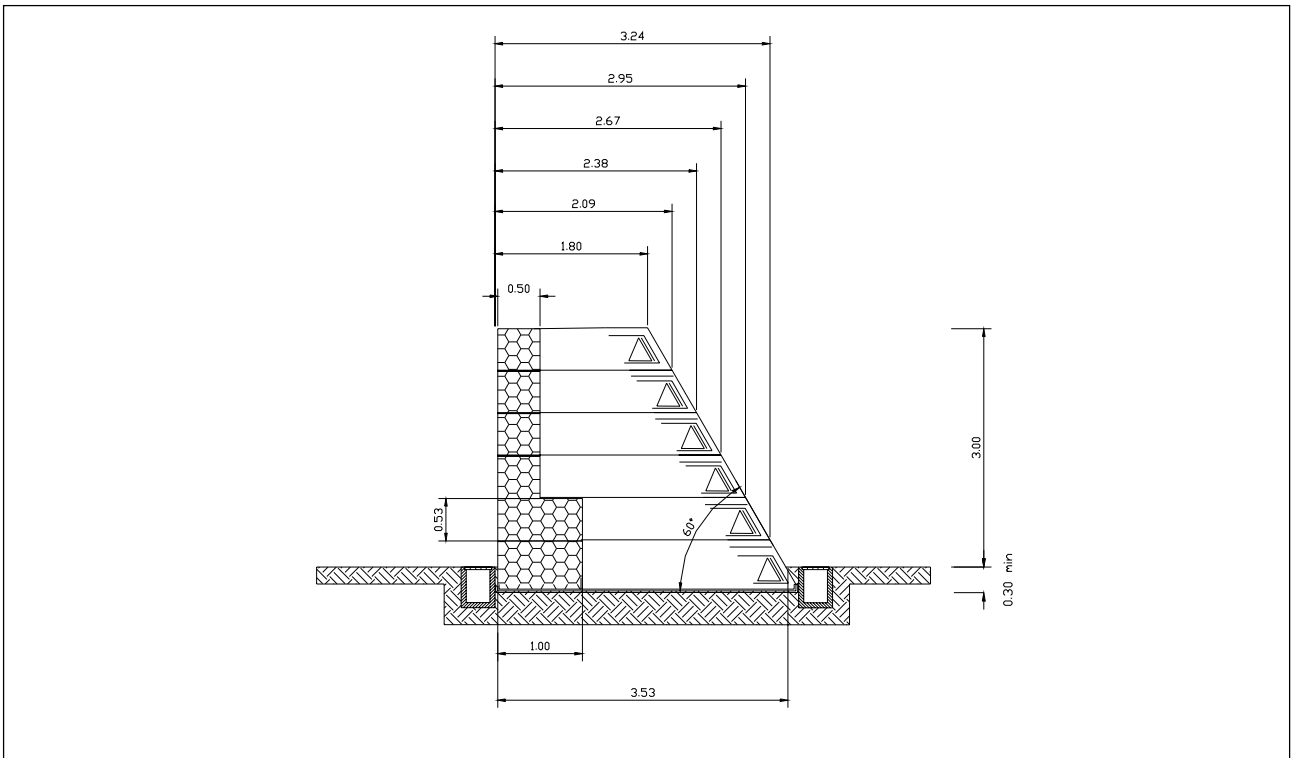
Figure 11 Dune arrangement with differentiated 60°/90° slopes, with vertical gabion faces

Figure 12 Photo showing the implementation of a test dune, with differentiated 60°/90° slopes, with vertical gabion faces

Penetration by Projection Test

This kind of test is clearly fundamental to ascertain the effectiveness of the dune as a protection system. The calculation procedure has to establish the dune's optimal geometric requirements to ensure its function of intercepting vehicles running off the road, eventually with their load.

The test was carried out using numerical simulation models and showed that the dune can be erected at a minimum distance of 6.5m from the foot of the slope, so that impact occurs with the vehicle fully at ground elevation, after coming to earth.

Embankment Stability Test

This test is one of the usual ones for embankments, and has to ascertain whether the standard section geometry provides a sufficient safety factor against collapse, in relation to the resistance to shearing stress of the material employed.

The structures have been sized so as to obtain safety factors that are always higher than the minimum foreseen for mixed works – earth and reinforcements (M.D. 11/03/1988). In particular, for the sections indicated, the test was carried out distinguishing cases of internal stability (checking of necessary length and spacing of reinforcements to guarantee that the reinforced dune would be sufficiently compact and resistant to internal actions caused by loads) and overall stability (checking of the dimensions of the structural mass against external slips).

Break-through Test

Assessment of the local effects on embankments subjected to high propulsive loads is very complex, because so far no final definition has been given to the dissipation of energy inside the embankment and to structural collapse.

The predominant collapse mechanism is perforation (whereas the effects of overturning and slipping are almost negligible). As a design parameter therefore, the thickness of the reinforced earth embankment is fundamental.

The dynamic load is generated by propulsive forces produced on earth-object contact. Like what happens to road barriers, the load curves (F,t) assume a triangular trend with a median peak much more accentuated for granular materials rather than cohesive materials.

When a body impacts the ground, contact pressure occurs at the body-ground interface. If the body's resistance is higher than the said pressure (which it certainly is in this case), it penetrates the ground, by breaking into it locally. The body comes to a halt when the kinetic energy it possessed at the initial instant of impact has been completely spent in overcoming the ground's penetration resistance and in the deformation of the earth mass adjacent to the impact area.

The vehicle's impact on the dune thus generates a strong local piercing effect; the mark left by the impacting body will be mainly associated with permanent deformations, with a negligible elastic component.

The embankment's role is to bring the loads to a halt, thanks to the dissipation of kinetic energy resulting from the work of moving the soil.

During the impact, there must consequently be a sufficient volume of soil to be deformed without being broken through. In practical terms, however, embankment construction requirements (easy compaction of filling material) are for top thicknesses of over one metre.

A preliminary penetration calculation (z) has been made based on the transversally applied forces to define "design impact", on the basis of which penetration can be determined. If energy conservation is provided for (equal to the deformation performed by the collision force with the kinetic energy possessed at the moment of the vehicle's impact), the result is:

$$z = \frac{m \cdot v^2}{2 \cdot F_{mean}}$$

where:

F_{mean}	=	mean collision force;
z	=	penetration depth;
m	=	mass of vehicle or its load;
v	=	speed of vehicle or its load at moment of impact.

The most serious condition is that of the trailer of a heavy vehicle with a full load of 220 kN, running off the road at a speed of about 100 Km/h at an angle of about 20°. The said transversal force graphs provide two major sets of values for estimated impact forces. In view of the deformable nature of dune structures, the effective value of the force tends to be nearer to the lower limit (Hirsch).

Using these values, penetration of 1.4m can be calculated for a whole vehicle, and 0.9m for the load alone, becoming detached after collision.

In the literature, the predictive method proposed by Kar (1978 and 1979) consists of a set of empirical formulas to estimate maximum penetration depth for impacting bodies. This procedure, based on experiments to analyse the effects of military projectiles on underground structures, is not easy to apply to reinforced earth embankments because the key parameter identifying the soil is its resistance to simple compression, which cannot be easily defined for the soils utilised in constructing the embankments.

However, a comparison can be made between the results previously obtained and those obtained by applying this method, used in some cases to estimate penetration in boulder protection embankments. In particular, this describes penetration z = f(Z), where Z is the penetration parameter, as follows:

$Z = (z/2d)^2$ if $z/d \leq 2$
$Z = (z/d) - 1$ if $z/d > 2$

The parameter Z can be obtained by the following ratio:

$$Z = \frac{27183}{\sqrt{Y}} \cdot N \cdot \left(\frac{E}{E_s}\right)^{1.25} \cdot \frac{m}{d^{2.31}} \cdot \left(\frac{v}{1000}\right)^{1.25}$$

where:
Y	=	simple compression resistance of the soil (kN/ m^2);
N	=	shape factor for the impacting body (ranging from 1 for a pointed body to 0.72 for a flat body);
E	=	Young's modulus for the impacting body (kN/m^2), in this case assumed to be $5 \cdot 10^7$;
E_s	=	mean Young's modulus for steel = 206850000 (kN/ m^2)
m	=	mass of impacting body (kg)
v	=	transversal component of impact speed (m/s)
d	=	maximum diameter of the impact impression (cm)

By establishing appropriate values for the whole vehicle and for its load, the penetration depths obtained are 1.5 m and 0.8 m, which are clearly very similar to those reached by the simple method, applying the energy conservation principle.

The estimated penetrations are thus less than the corresponding dune sections. Furthermore, for boulder protection dunes, the semi-empirical equation of Kar has been found to be very conservative as compared to live tests, more especially because the behaviour of the reinforced soil is better under dynamic conditions than under static ones.

In the assumption of variable elasto-plasti and dynamic load behaviour over time, the propulsive force can be calculated, exploiting the penetration calculated using Kar's formula, as per the following formula:

$$F_{max} = K \cdot \frac{m \cdot v}{T}$$

Where K =2.022 and T =3.335·(z/v)   (T = impact duration in seconds)

For the whole vehicle, Fmax equals roughly 750kN, while for the load only Fmax equals about 400kN. These values can be compared with those indicated in the graphs based on Hirsch's estimates, where they are respectively 900kN and 450kN.

Summit Testing

The summit of the dune is the only point at which it is not possible to apply the same assumptions or calculations for the dune, used to describe its static behaviour following a collision.

It consists of a "header" and a "collaborating zone", as indicated below:
- the current section of the dune is completed by a "header" with a vertical profile, suitably located to guarantee maximum closure of the gap corridor and joined below the ground elevation like the dune itself. This "header" may be produced in various ways, such as wire-netting gabions filled with stones, r. c. structures, reinforced earth structures, etc;
- the "collaborating zone" of the reinforced earth dune is appropriately joined to the "header" by suitable connecting structures and reinforced by longitudinal reinforcements of the same length as the entire "collaborating zone", so as to provide a single structure which will behave like a monolith and, in the event of collision, involve a sufficient volume of the dune to ensure that the protection structure does not slip towards the AV line.

The length of the "collaborating zone" and the connecting structures have been verified by balancing the forces, considering only the longitudinal component of the total impacting load on the summit, applied to the barycentre of the "header".

R. C. WALLS

Structures on Direct Foundations

This kind of protection structure consists of r. c. walls erected in the AI or adjacent to the AV embankment, erected between two joints continuously over the ground space. This is the simplest kind of r. c. structure, and can also be used as a retaining wall for the railway embankment.

The structures are all designed with a top thickness of at least 45 cm and a wall slope of 1/10, similar to the original railway design for retaining walls and walls below the AV embankment.

Breakage tests have been carried out for these structures, using the same criteria as for the road barriers (Montepara 1990): piercing tests, tests on section elements under greater stress, and overall stability tests for the protection structures from joint to joint.

Structures on Pile Foundations

This kind of structure consists of r. c. walls erected at the top of the railway embankment, constructed on drilled helical piles with a diameter of ø800 and a centre-to-centre distance of 6.00 m, united by a crest beam. Their peculiarity lies essentially in that they can be erected, without excessive construction costs, even when the railway embankment has been completed and causing limited interference with other structures foreseen by the design. Furthermore, such a design choice derives naturally from the foundation study for the noise barriers on piles, widely used along the original project section of the AV line.

The said structures have been subjected to piercing tests, tests on section elements under greater stress, and resistance tests for the foundation structures (piles).

ENVIRONMENTAL MITIGATION FOR THE SAFETY STRUCTURES

The construction features and sizing of the safety structures have necessitated architectural and environmental interventions to insert the structures in their territorial context. For this purpose, specific landscaping guidelines have been drawn up to identify eventual mitigation of the impact of the dunes and walls.

The project design was first examined: landscaping interventions foreseen for the enclosed area between the AV line and the motorway, and the safety structures, grouped into 10 macro typologies, according to their formal type. Having identified the compositional elements – with particular reference to the view from the motorway, essentially highlighting the linearity of the structures and the detail of the headers at the numerous gaps -, the visual impact was then examined, an impact differentiated by the height of the structure erected in the enclosed area, of the aesthetic work to be made on it, as well as the relative heights of the railway and motorway embankments.

In a flat and monotonous landscape, with variations due to man's intervention rather than to any exceptional natural elements, the railway embankment already constitutes a considerable barrier to the view towards the horizon, making it effectively impossible to see in that direction.

The facts identified during analysis also highlighted the extreme variability of the structures, both in type and spread: on the average, three structural macro-typologies alternate every kilometre, thus limiting the view from the motorway and making it fragmentary and discontinuous.
The proposed mitigation works have therefore given preference to the natural tendency to simplicity, making serial, discreet interventions of a limited mark, so as to tie together the already numerous elements involved (pylons, barriers, fencing, guard-rails, ground swellings, systems, etc.).

The guidelines, forwarded to Italferr for a definition of the mitigatory solutions to be submitted to the Environmental Observatory (Organ appointed by the Ministry for the Environment to supervise the safeguarding of the environment for the Milan-Bologna AV project), identify three different "thematic" solutions. In order to minimise the visual impact, three basic criteria have been identified for the interventions, in order to ensure homogeneity and maintain the natural trends of the landscape:
- DYNAMISM instilled into the infrastructures that flank, cross and entwine with each other along the line, to which must be added the speed and continuous movement of traffic. The lines introduced by the project accompany and accelerate movement on this infrastructure dedicated to speed. From concrete structures to vegetation arrangements, everything must be subject to the concept of dynamism.
- NATURALNESS, featuring components of little construction, on principle vegetation, but including structures with an organic aspect, recalling natural elements.
- SIMPLICITY, with the intent of creating uniform surfaces, tranquil, easy to read and comprehend.

A single criterion was aimed at, subdividing the works among the alternatives proposed within the context of the criterion chosen.

Mitigation of the dunes is essentially implemented by turfing and shrub plantations. Interventions involve both the sides and summits of the structures. The various "thematic" solutions are carried out through the arrangement and choice of shrubs and by the spacing of shrub-covered areas and those covered only with turf. In choosing the vegetation, the specifications of the Ministry of the Environment have been taken into account, as well as the safety constraints relating to the two transport infrastructures, microclimatic conditions, exposition, and the agronomic characteristics of the soil.

The following has been considered concerning wall interventions:
a) application of strips of Nordic pinewood, pressure-treated in autoclave to render them imputrescible and non-deformable. According to requirements, the strips can create linear or woven designs, or be combined with vegetation. The profiles are fixed using steel nogs.
b) surface treatment (texturing) using an elastic sheet matrix, placed inside the formworks for pouring the concrete. Various designs have been proposed according to the effect intended.
c) application of protective coloured paints on the concrete, in cases where walls have already been constructed. Colours can be chosen according to the main crops grown in the various areas.

Having defined the range of possible solutions, assessment data were lastly provided, not strictly concerned with landscaping the works, but rather with technical and economic aspects (adaptability to the various types of structure, easy implementation, maintenance and durability, cost, etc.).

CONSISTENCY OF THE WORKS

The main civil works concerning the safety of the AV line are indicated below.
- wherever the area is sufficiently wide (status from 20 to 80 m, length about 45.5 km), reinforced earth dunes will be erected with varying widths and heights, providing special summits where gaps have to be left; surmountable earth dunes will also be erected;
- when the area is from 6 to 20 m wide (about 53.5 km in length), either reinforced earth dunes or r. c. walls will be erected, with variable dimensions, which, according to need, may act to retain the railway embankment and/or protect from any vehicle running off the motorway;
- partial demolition of railway embankments already carried out, wherever retaining walls have to be erected;
- embellishment of walls already erected to adapt them to the new geometry required by the Safety Plan;
- realisation of the definitive service road inside the Enclosed Area, together with new crossing works;
- archaeological probes in areas not previously expropriated.

The total length of the safety structures is about 99 km, as detailed below:
- about 20.00 km of r. c. walls, either retaining walls or below the railway embankment (including r. c. walls on piles)
- about 9.00 km of r. c. walls in the enclosed area h=3.00 m
- about 5.75 km of r. c. walls in the enclosed area h=1.90 m
- about 1.75 km of reinforced earth terminal dunes h=1.90 m with 80°- 80° sides
- about 41.50 km of reinforced earth dunes h=3.00 m with 60° -60° sides
- about 17.00 km of reinforced earth dunes h=3.00 m with 60° -90° sides
- about 4.00 km of reinforced earth dunes h=3.00 m with 60° -90° sides -2/3

CONCLUSIONS

The design decision to contain the relative distance between important transport infrastructures in order to decrease their impact on the environment may lead to serious safety problems.

In the specific case of the Milan-Bologna section of the high-speed railway line (AV), it has led to an in-depth study of the interactions generated by the two infrastructures, with results that are in part unpredictable at a first approach. Its application to design has involved the inclusion of the protection structures described in this article, sized so as to reach the safety level required by the Customer.

The problem tackled could provide useful references for a hoped-for generalisation of the problem, with the aim of achieving an adequate standard of design reference.

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