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Skew Effects and External Wall Stiffening in Reinforced Concrete Box Culverts: A Critical Review of Experimental, Field and Numerical Evidence

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Abstract
Reinforced concrete box culverts are the most numerous cross-drainage structures on road networks, and a growing share of them are built at an angle to the carriageway because of stream alignment, land constraints or existing services. Design practice for these skew boxes still leans on two-dimensional rigid-frame analysis, while external lateral buttresses that stiffen the side walls have been suggested but scarcely examined. This paper presents a critical review of experimental, field and numerical research relevant to the structural behaviour of straight and skew box culverts, drawing mainly on work indexed in Scopus, ScienceDirect and the ASCE Library. A total of 56 technical studies, supported by 5 design codes, are organised into seven themes: load rating and three-dimensional modelling, live load dispersion through fill and pavement, earth pressure and soil-culvert interaction, shear and force flow in skew slabs, culvert-specific skew studies, stiffening and strengthening measures, and dynamic response. The evidence shows that full-scale tests have only recently begun to quantify skew effects in culverts, that shear concentrates at the obtuse corner of skew slabs, and that the relative stiffness of box and soil controls the earth pressure the box attracts. It also shows that skew and wall stiffening have been studied in isolation, that culvert data beyond 30 degrees of skew are scarce, and that strengthening studies rarely report how added stiffness shifts demand to the base slab. A comparative modelling framework built on two normalised indices, a skew amplification factor and a buttress efficiency ratio, is proposed to close these gaps, together with a prioritised agenda covering continuum soil modelling, buttress optimisation, laboratory validation and seismic assessment.

Keywords: *Box culvert; Skew angle; Lateral buttress; Soil-structure interaction; Live load distribution; Finite element modelling; Review*

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I. Introduction

Small structures carry a large share of the risk on any highway. A blocked or distressed culvert can close a road as effectively as a failed bridge, yet culverts are usually designed from standard drawings and receive far less inspection attention than bridges. Among the forms in common use, the cast-in-situ or precast reinforced concrete box with one or more cells is preferred for clear spans of roughly two to eight metres, since it can be founded on modest soils, cast in a few lifts and extended without difficulty when the road is widened [1]. In the United States, culverts of bridge length make up a substantial part of the national bridge inventory, and a sizeable body of recent work on load rating has shown that the simple frame models used for their design and assessment often misjudge how these buried boxes actually carry load [2], [3].

Two practical conditions make the problem harder. The first is skew. When a stream, canal or drain crosses the road at an angle, the barrel is laid parallel to the watercourse and the box becomes a parallelogram in plan. Vertical load then seeks the stiffest route between supports, which in a skew slab runs towards the obtuse corners, so twisting moments develop and the reactions along the walls become uneven [4], [5]. Codes for small bridges in India and North America give little explicit guidance on when such geometry needs three-dimensional analysis, and a recent experimental programme confirmed that design practice for skew culverts varies widely between highway agencies [6].

The second condition concerns stiffening. Counterforts have long been added to cantilever retaining walls to shorten the span of the stem, and haunches and extra corner steel are known to raise the capacity of box sections

[7], [8]. A lateral buttress cast against the outer face of a culvert side wall is the natural extension of this idea to a buried box. It can reduce wall bending under high lateral earth pressure, but in a closed, statically indeterminate frame any change in member stiffness also redistributes moment and shear to the other members. Whether that redistribution helps or harms a skew box has not been documented.

This review was prepared to support a comparative investigation of straight and skew box slab culverts with and without lateral buttresses. Its objectives are (i) to consolidate the experimental, field and numerical evidence on the behaviour of skew boxes and on stiffening measures; (ii) to examine the modelling assumptions on which that evidence rests; (iii) to identify the gaps that stand in the way of a rational design approach for buttressed skew culverts; and (iv) to propose a consistent framework and research agenda for closing them. Section 2 describes how the literature was collected and Section 3 sets out the structural idealisation used in practice. Sections 4 to 10 review the evidence by theme, Section 11 compares modelling practice, Section 12 brings the findings together and identifies research gaps, Section 13 proposes a comparative framework, and Section 14 concludes.

II. Review methodology

The literature was gathered from Scopus, ScienceDirect, the ASCE Library, the Transportation Research Board TRID database and Google Scholar, supplemented by backward searching of the reference lists of retrieved papers. The search terms and selection rules are listed in Table 1. Peer-reviewed journal papers and refereed conference papers published between 2000 and 2026 form the core of the review. Earlier or non-journal sources were kept only where they remain the reference work on a topic, as with the design loading study of Kim and Yoo [9], or where they supply the only experimental evidence available, as with the full-scale skew culvert tests reported by Murrah [6]. Two preprints released in 2026 were included because they deal directly with skew culverts, but their findings are treated as provisional. Where the full text could not be accessed, the abstract, introduction and conclusions were used, and the study is cited only for points that those sections support.

Table 1. Review protocol.

Item	Description
Databases	Scopus, ScienceDirect, ASCE Library, TRB TRID, Google Scholar, with backward reference searching
Core search terms	box culvert; buried structure; skew; skewed slab; obtuse corner; live load distribution; earth pressure; soil-structure interaction; induced trench; haunch; counterfort; buttress; strengthening; seismic; finite element
Time window	2000 to 2026, with earlier landmark studies retained where they remain the standard reference
Inclusion	Peer-reviewed journal papers, refereed conference papers, agency research reports and theses containing original test data
Exclusion	Unrefereed web articles, papers without a stated method, duplicate reports of the same dataset
Coding variables	Theme, method, skew range, span and cover, soil representation, response quantities reported

The retained studies were coded by theme, by method (experimental, field monitoring, numerical, analytical or review) and by the structural variables they considered. Fig. 1 shows how the 56 technical sources are distributed among the seven themes and across publication periods. Two features stand out. Earth pressure and soil-culvert interaction account for the largest share of the work, and almost every culvert-specific skew study has appeared from 2022 onward, which signals both the novelty of the topic and the limited depth of evidence on it.

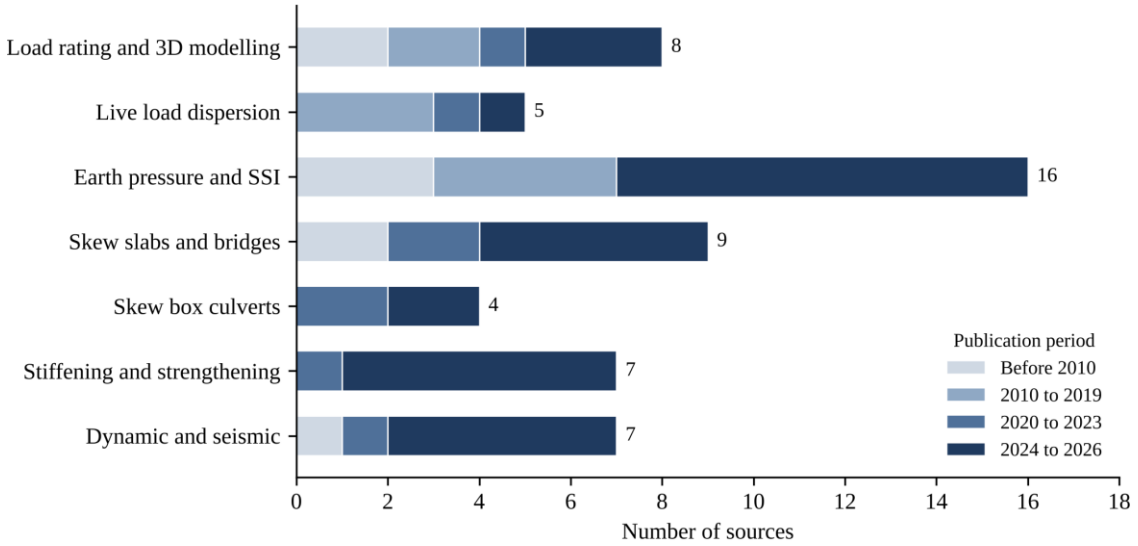


Fig. 1. Distribution of the reviewed technical sources by theme and publication period.

III. Structural idealisation and code background

Box culverts are conventionally analysed as closed rigid frames of unit length, with the top slab, walls and base slab represented by line members and the surrounding soil replaced by applied pressures [1], [10]. In Indian practice, loads and load combinations follow IRC:6 [11]. Vehicular loads such as IRC Class 70R and Class A are dispersed through the cushion before being placed on the top slab, and member design follows IRC:112 [12], with IS 456 [13] used for components outside the scope of the bridge code. The base slab is usually treated as resting on a uniform or elastic reaction, and the walls carry at-rest earth pressure together with a live load surcharge.

This idealisation contains three assumptions that matter for the present topic. Load is assumed to travel in the plane of the frame, which is reasonable for a straight box under uniform fill but not for a skew box, nor for concentrated wheel loads at shallow cover. The earth load is assumed to depend only on fill height and unit weight, whereas the actual load depends on the relative stiffness of the box and the surrounding soil. Geotechnical studies usually express this through a soil-culvert interaction factor [9], [14]:

$$F_e = W_a / (\gamma B_c H) \quad (1)$$

where W_a is the vertical load acting on the box per unit length, γ is the unit weight of the fill, B_c is the outside width of the box and H is the fill height above the top slab. Values of F_e above unity indicate that the box attracts load through negative arching, which is typical of rigid boxes in embankment installations [9], [15]. The third assumption is that the wall-to-slab joints are fully rigid. Full-scale tests on cast-in-place skew boxes found these joints to behave almost exactly as rigid connections [6], which supports the assumption for monolithic construction, though older boxes with lighter corner detailing may not satisfy it [2].

IV. Load rating, field testing and three-dimensional modelling

Much of the recent research momentum on box culverts has come from load rating. Agencies in the United States found that older cast-in-place boxes designed for lighter trucks frequently return rating factors below unity under current specifications, even though they show no distress in service. Wood et al. [3] compared two production-oriented demand models with live load test data from three instrumented culverts at four cover depths and found that the accuracy of the predicted load magnitude depended chiefly on how each model attenuated live load through the soil. A later refinement calibrated that attenuation to the depth of each critical section rather than to the cover depth alone, which moved the predicted demand towards more uniform accuracy across sections [16].

Field-calibrated three-dimensional models have since become the standard tool for resolving this mismatch. Gheitasi et al. [17] load-tested in-service Texas culverts, used the measurements to calibrate three-dimensional finite element models that included soil-structure interaction, and then used those models to refine the two-dimensional models employed in rating. Peiris and co-workers load-tested eighteen cast-in-place culverts in Kentucky with one to four cells and found that maximum top slab strains fell below about ten microstrain, a level at which live load effects can be neglected, once the fill exceeded about 3.05 m [18], [19]. The state-of-the-art review by Sabouri Ghannad et al. [2] compared national and state rating procedures and showed, through worked single-cell and multi-cell examples, how strongly the rating depends on the assumed soil interaction and on the analysis model.

Earlier finite element work had already pointed in the same direction. Garg and Abolmaali [20] reproduced full-scale tests on precast boxes with three-dimensional shell and solid models, and Abolmaali and Garg [21] identified shear near the haunch as the action governing the capacity of precast boxes under wheel loads. The relevance of this body of work to skew culverts is direct. A plane frame cannot represent twisting of the slabs, uneven reactions along a skewed wall or load sharing between cells, so the arguments made for three-dimensional modelling in load rating apply with greater force wherever the geometry departs from the orthogonal.

V. Live load dispersion through fill and pavement

The share of a wheel load that reaches the top slab depends heavily on the cover and on the pavement above it. Orton et al. [22] field-tested ten bridge-class culverts with fill depths between 0.76 m and 4.1 m and confirmed that the live load effect diminished steadily with depth, while both the AASHTO LRFD and the older Standard Specifications overestimated the measured response. Acharya et al. tested a single-cell box beneath concrete pavement, a concrete shoulder and unsurfaced fill [23], and then built a three-dimensional finite difference model from the measurements [24]. Their parametric study showed that vertical pressure on the roof decreased as pavement thickness, fill depth and span increased, and that the AASHTO distribution methods were overly conservative for low-fill boxes under rigid pavement.

Katona [25] extended the AASHTO load-spreading approach to account for the stiffness of the pavement layers and demonstrated that neglecting the pavement can understate the rating of buried culverts by a wide margin. Firoj et al. [26] treated the question probabilistically, quantifying the model uncertainty of the AASHTO distribution model for moderately buried boxes and showing that the simple spread-angle idealisation can depart markedly from refined estimates.

Two points follow for skew culverts. The IRC dispersion rules [11], like their AASHTO counterparts, were derived for orthogonal geometry, and on a skew slab the dispersed patch overlaps the obtuse corner region differently depending on the direction of travel. Live load is also most influential at shallow cover, which is the very condition under which skew effects on the top slab are expected to be most visible. Studies that vary cover and skew together are of particular value for this reason. Philip et al. [27] followed this route for two-cell road-under-bridge culverts and found that skew effects on longitudinal braking and traction forces were most pronounced at low fill heights (Section 8).

VI. Earth pressure and soil-culvert interaction

The vertical load on a buried box can differ substantially from the weight of the soil prism above it. Kim and Yoo [9] used finite element analyses with hyperbolic soil models to evaluate deeply buried boxes under embankment and trench conditions and identified the parameter combinations that make imperfect (induced) trench installation effective. Bennett et al. [15] instrumented boxes beneath high embankments and found vertical loads exceeding the soil prism weight, and Pimentel et al. [28] showed through combined numerical and experimental work that soil pressures and the nonlinear response of the box are closely coupled and should be considered together at the design stage.

Centrifuge testing has clarified the role of relative stiffness. Abuhajar et al. [29] tested model boxes of two wall thicknesses in sand at different relative densities, and their companion numerical study [14] showed that interaction factors fall at the centre and rise at the edges of the top slab as the box becomes more flexible relative to the soil. McGuigan and Valsangkar [30] measured pressures on boxes in several induced trench configurations, and field data from a double-cell cast-in-place box under more than 25 m of fill confirmed the load reduction available from a compressible zone [31].

Field evidence from shallower installations continues to question design pressures. Sanderson et al. [32] monitored two Iowa box culverts over long periods and recorded earth pressures well above the design values, together with longitudinal cracking on the underside of the top slab. Wang et al. [33] measured a nonlinear vertical pressure distribution on the top slab of hinged prefabricated boxes, Ma et al. [34] revised the soil column method for high-fill culverts by allowing the sliding interface to incline, and Chai et al. [35] proposed a method for the stress increase beneath boxes located beside embankments.

A further group of recent studies has examined load reduction with compressible inclusions. Geogrid and expanded polystyrene (EPS) systems lower crown pressure, but long-term analyses show that side wall pressure can grow with time as the surrounding soil creeps [36], [37]. The thickness of the EPS layer controls most of the benefit [38], and the outcome is sensitive to trench geometry [39] and to the stiffness of the founding soil [40]. The lesson that carries over to the present topic is that any change in the stiffness of the box relative to the soil redistributes pressure between its faces. A projecting buttress does exactly this. It stiffens part of the wall, changes the boundary against which the backfill is compacted, and may attract or shed lateral pressure locally. None of the reviewed studies has quantified that effect.

VII. Shear and force flow in skew slabs

Skew concrete slabs have been studied far more than skew culverts, and they offer the closest analogue for the top and base slabs of a skew box. Menassa et al. [4] analysed 96 simply supported slab bridges by finite elements and found that the longitudinal moment changed little up to a skew of about 20 degrees, then fell to roughly three quarters of the straight value between 30 and 40 degrees and to about one half at 50 degrees, with the AASHTO procedures overestimating the moment by a growing margin as skew increased. Huang et al. [5] field-tested and modelled a 60 degree continuous composite bridge and showed that its transverse load distribution was not captured well by the empirical code formulas. The broad message from bridge decks is that skew lowers longitudinal bending but raises shear, twisting moment and reactions near the obtuse corner. Fig. 2 illustrates this change in load path schematically for a single-cell box.

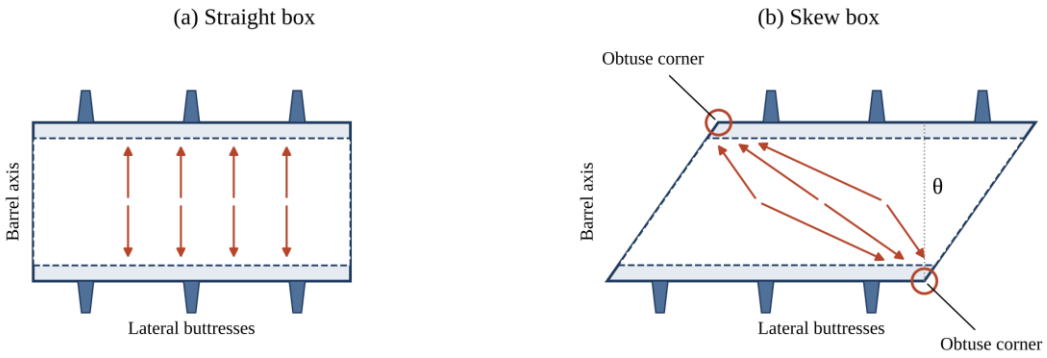


Fig. 2. Plan idealisation of (a) a straight and (b) a skew single-cell box culvert with external lateral buttresses, showing the diagonal load path towards the obtuse corners (schematic, not to scale).

Recent experimental work at Delft University of Technology has given this message a firmer basis. Lu et al. [41] reported fifteen tests on five half-scale slab members loaded near the edge and found that shear capacity decreased as skew increased, with the obtuse corner as the critical region and the reinforcement layout having little influence on capacity. The full analysis [42] proposed an assessment approach in which the peak shear stress from linear finite element analysis is averaged over a longer integration length. Lipari reviewed design and assessment methods for skew slabs [43] and then examined how the second-generation Eurocode 2 provisions can be extended to them [44]; for two skew railway decks, the new code returned greater design shear resistance than its predecessor when the mechanical shear span was used in place of the effective depth.

Numerical studies add detail on local sensitivity. Ibrahim et al. [45] modelled thirteen 45 degree skew slabs with openings and found the largest loss of capacity when the opening lay near an obtuse corner, confirming that this region carries a disproportionate share of the load. Studies of skew girder systems report the same pattern at the supports. Lan et al. [46] found that bearing forces in skewed T-girder bridges rose appreciably with skew, and Agarwal and Singh [47] observed that skew influenced the dead load response of prestressed box girders more strongly than the live load response. None of these studies deals with a closed box, yet together they identify the obtuse corner, and the support line beneath it, as the places where a skew culvert is most likely to be governed.

VIII. Studies on skew box culverts

Research aimed specifically at skew box culverts is thin and recent. Philip et al. [27] examined two-cell boxes for road-under-bridge use with skew angles from 0 to 75 degrees in 15 degree steps and fill heights from 2 to 10 m, using Indian railway and road loading provisions. Some load components were insensitive to skew, while longitudinal forces from braking and traction increased with skew, especially at low fill heights. Mishra and Pendharkar [48] varied span-to-height ratio and skew in STAAD.Pro models of two-cell boxes and recommended keeping skew below about 17 degrees for economy. That study appeared in a journal outside the major indexes and is useful mainly as a reflection of current design-office practice.

The most informative evidence so far comes from full-scale laboratory testing at Auburn University. Murrah [6] tested three cast-in-place specimens with a 3.05 m (10 ft) clear span and identical reinforcement at skews of 0, 30 and 60 degrees under simulated wheel loading. Skew had little effect on overall stiffness, service behaviour or ultimate strength, because the skewed specimens developed two-way bending that engaged the

longitudinal slab steel and the integral parapet beams. The failure mode, however, changed from beam shear at 0 and 30 degrees to punching shear of the slab at 60 degrees. The author concluded that the common agency practice of doubling reinforcement in skewed regions was unnecessary for the configurations tested.

Two finite element studies from the same research group, released as preprints in 2026, examine the edge beam that runs along the culvert opening. The first modelled culverts with skews of 0 to 60 degrees in ABAQUS using shell elements, supported by a solid model for local behaviour, and concluded that an edge beam with adequate shear reinforcement is essential to maintain ultimate capacity in skew layouts [49]. The second derived stiffness from load-deflection responses at several positions along the barrel and showed that the edge beam acts as a local boundary stiffener whose influence decays towards mid-length while the global load transfer mechanism stays unchanged [50]. These results await peer review, but they matter here because they are the only published work that adds a stiffening element to a skew culvert and tracks how its effect varies along the barrel.

Read together, the culvert-specific studies suggest that skew is less damaging to global stiffness and strength than the slab bridge literature might imply, largely because the closed box and its edge members offer alternative load paths. They also show that the mode of failure and the local demand near the obtuse corner change at high skew, with the transition lying somewhere between 30 and 60 degrees. Table 2 summarises the principal skew studies from both groups.

Table 2. Summary of principal studies on skew slabs, skew bridges and skew box culverts.

Ref.	Structure	Method	Skew range	Main finding
[4]	RC slab bridges	FE, 96 cases	0 to 50°	Longitudinal moment falls to about half of the straight value at 50°; code procedures conservative
[5]	Composite girder bridge	Field test and FE	60°	Empirical distribution factors inaccurate at high skew
[41]	Half-scale RC slab members	Laboratory, 15 tests	Several angles	Shear capacity falls with skew; obtuse corner critical
[45]	Skew slabs with openings	Validated FE	45°	Openings near obtuse corner most harmful
[44]	Skew railway decks	Code-based analysis	Case studies	Second-generation Eurocode 2 gives higher shear resistance
[46]	Skewed T-girder bridges	FE parametric	Varied	Bearing forces rise with skew
[27]	Two-cell RUB box culvert	Analytical	0 to 75°	Braking and traction forces rise with skew, more so at low fill
[6]	Single-cell CIP box culvert	Full-scale laboratory	0, 30, 60°	Little change in stiffness or strength; punching shear at 60°
[49]	Box culvert with edge beam	Shell and solid FE	0 to 60°	Shear reinforcement in edge beam governs capacity

IX. Stiffening and strengthening measures

Measures that alter the stiffness of a box have been studied almost entirely from the strengthening point of view. Waqas et al. [8] analysed boxes with different haunch geometries and additional diagonal bars and reported gains in load-carrying capacity of about 25 percent for the most effective combinations. The same group modelled carbon fibre reinforced polymer sheets on culverts weakened by water-induced corrosion and reported comparable gains [51]. He et al. [52] tested and modelled damaged boxes lined with glass reinforced plastic and found that the liner raised the ultimate load by about 67 percent and the initial stiffness by a factor of about 3.6. Mun et al. [53] installed an internal strut and preloaded bolt system and raised the seismic capacity of RC boxes by close to 58 percent. Bu et al. [54] approached the problem from the opposite side, testing scaled top slabs with multiple openings and showing with validated nonlinear models that the size and arrangement of the openings govern stiffness and capacity.

Outside the culvert field, the closest analogue to a lateral buttress is the counterfort of a retaining wall. Scaled tests on prefabricated counterfort walls by Luo et al. [7] showed that counterforts redistribute bending between the stem and the base and concentrate stress at the stem-counterfort joint. The edge beam studies discussed in Section 8 [49], [50] provide a second analogue, showing that a stiffening member at the boundary of a box raises local stiffness without changing the global load transfer mechanism.

Table 3. Studies on stiffening, strengthening and local geometric modification of box structures.

Ref.	Measure	Method	Reported effect	Effect on other members reported
[8]	Haunch geometry and diagonal bars	Nonlinear FE	Capacity gain of about 25%	No

Ref.	Measure	Method	Reported effect	Effect on other members reported
[51]	CFRP sheets on corroded box	Nonlinear FE	Capacity recovered and raised	No
[52]	GRP liner in damaged box	Laboratory and FE	Ultimate load up about 67%, initial stiffness about 3.6 times	Partly
[53]	Internal strut with preload bolts	Laboratory and FE	Seismic capacity up about 58%	No
[54]	Multiple openings in top slab	Laboratory and FE	Stiffness and capacity depend on opening layout	Partly
[7]	Counterforts in retaining wall	Scaled tests	Moment redistributed between stem and base	Yes
[50]	Edge beam along opening	Linear FE	Local stiffening that decays along barrel	Yes (reactions)

Two observations emerge from Table 3. Every study reports the benefit to the member being strengthened, whether in capacity, stiffness or crack control, yet very few report what happens to the rest of the frame. In a statically indeterminate box, moments distribute in proportion to relative stiffness, so a buttress that stiffens the side wall will draw moment from the adjoining slabs at the wall-slab joints and pass a larger share of the wall moment into the base slab. In a straight box this redistribution is symmetric and generally relieves the top slab. In a skew box the buttresses sit at an angle to the dominant diagonal load path (Fig. 2), so their effect on the base slab near the obtuse corners cannot be inferred from orthogonal reasoning. The base slab is for this reason the member most likely to suffer an adverse side effect, and it is also the member least examined in the strengthening literature.

X. Dynamic and seismic behaviour

Buried boxes have generally performed well in earthquakes, but racking failures of shallow rectangular underground structures, the best known being the collapse of Daikai station in 1995, made seismic soil-structure interaction a standard design concern [55]. Tsinidis et al. [56] reviewed field, centrifuge and shaking table evidence for tunnels and underground structures and emphasised how strongly racking demand depends on the flexibility ratio between the structure and the soil. Culvert-specific work has grown since then. Ozturk [57] showed that near-fault pulses and soil class strongly influence the response of three-sided underpass culverts, Wu et al. [58] tested a prefabricated box assembled from split components on a shaking table, and Hazem et al. [59] used the domain reduction method to show where the simplified NCHRP 611 procedure over- or underestimates internal forces.

Skew brings further complications. In skewed bridges, seismic loading induces in-plane rotation of the deck, raises the risk of unseating and concentrates damage near the corners [60], [61]. Whether a buried skew box undergoes a comparable rotational mode, and whether external buttresses would restrain or aggravate it by changing the stiffness seen by the soil, is unknown. These questions lie outside the static scope of most culvert design, but they show that the dynamic consequences of external stiffening will eventually need attention.

XI. Numerical modelling practice

The numerical studies reviewed above differ widely in how they represent the box, the soil and the boundary between them, and these choices determine whether results from different studies can be compared at all. Table 4 summarises the main options and their consequences for skew and buttress studies.

Table 4. Modelling choices in the reviewed numerical studies and their implications.

Aspect	Common options	Representative refs.	Implication for skew and buttress studies
Box members	Line frame; 4-node plate or shell; 3D solid	[20], [49], [54]	Plates capture twisting and membrane action at modest cost; solids are needed for local rib or edge behaviour
Soil	Applied pressure; Winkler springs; continuum (FE or FDM)	[14], [17], [24]	Springs cannot reproduce arching or pressure redistribution around a projecting rib
Interface	Fully bonded; frictional contact	[9], [28]	Wall friction alters the vertical load attracted by the box
Material	Linear elastic; nonlinear concrete with cracking	[8], [28], [52]	Linear models suit comparative service studies; capacity questions need nonlinear models

Aspect	Common options	Representative refs.	Implication for skew and buttress studies
Live load	Dispersed patch on slab; explicit wheel on soil surface	[11], [24], [25]	Patch rules were derived for orthogonal geometry
Validation	Code checks; field tests; laboratory tests	[3], [6], [17]	No validation data yet exist for buttressed skew boxes

Three practical points follow. Plate or shell elements placed at the mid-surface are adequate for comparing the global response of straight and skew boxes, provided the mesh is refined at wall-slab junctions and at buttress roots, but they cannot resolve local shear transfer where a thick rib meets a thinner wall [49]. Winkler springs give a more realistic base flexibility than fixed supports and suit parametric work, yet they cannot capture arching or the change in lateral pressure that a projecting rib induces, which continuum models can [14], [39]. The most important point for comparative work is consistency: the same mesh density, boundary representation and load positions must be kept across all configurations, or differences attributed to skew or buttressing may simply reflect modelling changes. The programs used in the reviewed studies include ABAQUS, ANSYS, SAP2000, STAAD.Pro, FLAC3D and CANDE, and the choice among them matters less than the consistency of these assumptions.

XII. Synthesis and research gaps

Taken together, the seven themes yield a consistent picture. The load rating literature shows that two-dimensional frames misrepresent buried boxes and that field-calibrated three-dimensional models are needed whenever geometry or loading departs from the simple case [2], [17]. The live load and earth pressure literature shows that the demand on the box is governed by cover depth, pavement stiffness and the relative stiffness of box and soil [14], [22], [32]. The skew slab literature identifies the obtuse corner as the region of concentrated shear and the support beneath it as the location of increased reaction [42], [46]. The culvert-specific skew studies indicate that a closed box tolerates skew better than an isolated slab, at least up to 30 degrees, but that local failure modes change at higher angles [6]. The stiffening literature shows that added stiffness raises member capacity but says almost nothing about where the displaced demand goes. Table 5 sets out the gaps that follow from this synthesis and the action each one calls for.

Table 5. Research gaps identified from the review and recommended actions.

No.	Gap	Current evidence	Recommended action
G1	Skew and wall stiffening never examined together in a box culvert	Separate studies of skew [6] and of stiffening [8]	Controlled comparison of straight and skew boxes with and without buttresses
G2	Little culvert-specific evidence beyond 30° of skew	One test series to 60°, one specimen per angle [6]	Parametric analysis in finer steps to at least 45°, then targeted tests
G3	Redistribution of demand to unstrengthened members rarely reported	Member-level results only [51], [52]	Report member-by-member changes, with the base slab examined explicitly
G4	Interaction of a projecting rib with the backfill unknown	Stiffness effects shown for inclusions [36], [39]	Continuum soil models with staged backfilling around ribs
G5	No code criteria for 3D analysis or stiffening of skew boxes	IRC:SP:13 and IRC:6 silent on skew limits [1], [11]	Develop skew thresholds and dispersion checks for IRC loading
G6	No validation data for skew boxes with external ribs	None	Scaled or full-scale laboratory tests
G7	Seismic response of skew and buttressed boxes unexplored	Studies on straight boxes and skew bridges [59], [61]	Nonlinear dynamic SSI analysis including skew and ribs
G8	No cost or constructability comparison	None	Quantity and life-cycle cost study for each configuration

XIII. Proposed comparative framework and research agenda

To address gaps G1 to G3 in a way that allows results from different studies to be compared, a framework is proposed that separates the effect of geometry from the effect of stiffening (Fig. 3). Four families of models are analysed under identical material, mesh, boundary and loading assumptions: straight without buttresses (S-NB), straight with buttresses (S-B), skew without buttresses (K-NB) and skew with buttresses (K-B), the last two at a series of skew angles θ. The straight unbuttressed box serves as the reference, and two normalised indices are used to interpret the results. The skew amplification factor expresses a response at skew angle θ relative to the straight box of the same family:

$$SAF_\theta = R_\theta / R_0 \quad (2)$$

where R is any response quantity, such as the peak moment in a member, the design shear at a critical section, a support reaction or the maximum deflection. The buttress efficiency ratio expresses the change produced by the buttress at a given angle:

$$BER_\theta = [(R_{NB,\theta} - R_{B,\theta}) / R_{NB,\theta}] \times 100 \quad (3)$$

in which the subscripts NB and B denote models without and with buttresses. A positive BER means that the buttress reduces the demand and a negative value means that it increases it. Because BER is evaluated member by member, it exposes the side effects that the strengthening literature seldom reports: at the same skew angle a buttress may yield a positive BER for the top slab moment and a negative BER for the base slab shear. Reporting SAF and BER for every member, rather than for the governing value alone, also allows the obtuse corner effects identified in Section 7 to be tracked separately from global trends.

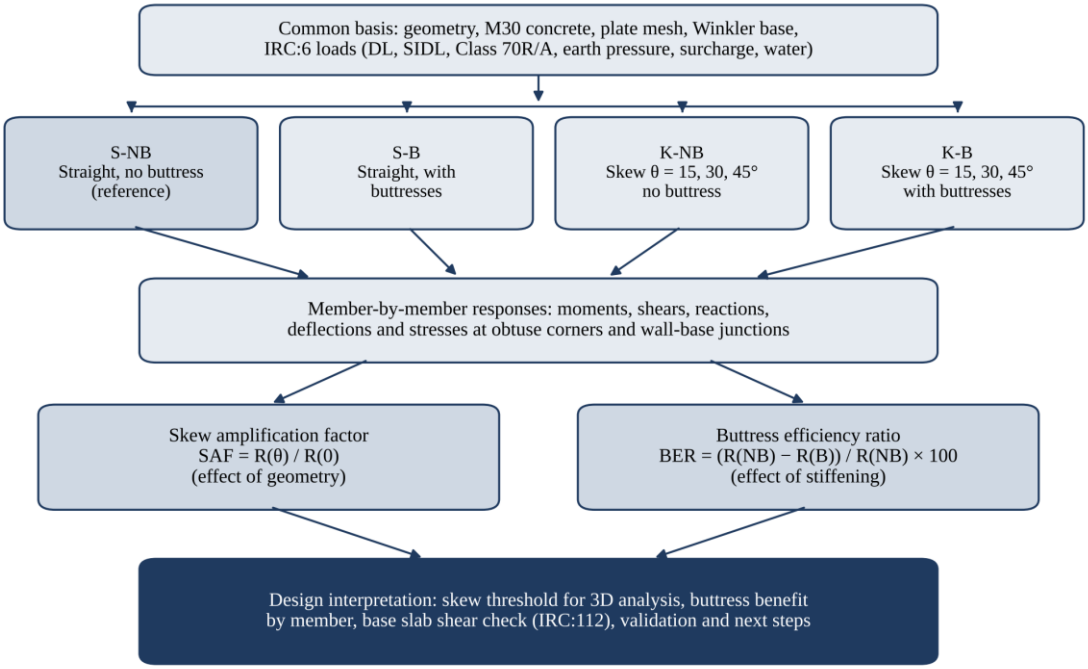


Fig. 3. Proposed comparative framework for evaluating straight and skew box culverts with and without lateral buttresses.

For Indian practice, the framework can be implemented with plate elements in STAAD.Pro or a comparable program, IRC Class 70R and Class A loading dispersed through the fill according to IRC:6 [11], at-rest earth pressure with live load surcharge on the walls, internal water pressure, and a Winkler base. Skew angles of 0, 15, 30 and 45 degrees cover the range usually met at canal and drain crossings, and finer steps can be added once the trends are established. Shear should be checked against IRC:112 [12] at the obtuse corners and at the wall-base junction, where the review suggests the critical demands will arise.

Beyond this first stage, the review points to six lines of work. Continuum soil models with staged backfilling are needed to capture arching and the change in lateral pressure around the ribs [37], [39]. Buttress spacing, depth and taper should be optimised separately for straight and skew layouts and compared against alternatives such as a thickened base slab or a haunched wall-base junction [8]. Nonlinear analysis should establish whether the shift to punching failure observed at 60 degrees [6] occurs at a lower angle once ribs are present. Scaled or full-scale tests of skew boxes with ribs are needed to validate the numerical trends. Seismic analysis with soil-structure interaction should examine whether ribs restrain or amplify racking and in-plane rotation [56], [59]. Finally, a quantity and life-cycle cost comparison is required so that any structural benefit can be weighed against the extra concrete, formwork and backfilling effort.

XIV. Conclusions

This paper reviewed 56 technical sources on the behaviour of reinforced concrete box culverts, with a focus on skew geometry and external stiffening of the side walls. The main conclusions are as follows.

(1) Two-dimensional rigid-frame analysis, still the basis of routine design, has been shown by field-calibrated three-dimensional studies to misrepresent buried boxes even in straight layouts. The case for three-

dimensional analysis is stronger still for skew boxes, in which twisting and uneven reactions cannot be captured in a plane frame.

(2) Live load effects diminish steadily with cover and become minor beyond about 3 m of fill, while pavement stiffness can reduce the demand considerably. The IRC dispersion rules have not been examined for skew slabs, where the dispersed patch interacts with the obtuse corner region.

(3) Earth pressure on a box is governed by the relative stiffness of the box and the soil, and field measurements have recorded pressures well above design values. Any element that changes wall stiffness, including a buttress, can be expected to redistribute pressure between faces of the box.

(4) In skew slabs, shear concentrates at the obtuse corner and capacity falls as skew increases. Closed box culverts appear more tolerant of skew up to about 30 degrees because of two-way action and edge members, but the failure mode shifts to punching at 60 degrees, and the angle at which this transition begins is not known.

(5) Stiffening and strengthening studies consistently report the benefit to the strengthened member but rarely the redistribution of demand to other members. In a skew box with lateral buttresses, the base slab near the obtuse corners is the member most likely to bear this side effect.

(6) The combined effect of skew and lateral buttressing is the clearest gap in the literature. The comparative framework proposed here, based on the skew amplification factor and the buttress efficiency ratio applied member by member, offers a consistent way to fill it and to build the evidence needed for design guidance.

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