Stream Restoration Series
Cross Vane

Authors: E.L. Hickman and T.M. Thompson, Biological Systems Engineering

ALTERNATE NAMES:

channel-spanning rock weir, U-weir, V-weir, A-vane

STRUCTURE TYPE:

rigid structure; grade control structure; river training structure

Cross vanes are channel-spanning structures that provide grade control, dissipate energy, deflect stream flow to the center of the channel, and create pools. A grade control structure stabilizes the stream channel by preventing changes in bed elevation at that point. It can also protect a streambank from undesirable erosion or migration when the erosion is caused by flows impacting the bank face. By protecting the bank from fluvial erosion, this structure promotes the overall stability of the stream cross-section. It is also used to create pools and to direct flows to the center of the channel upstream of bridge crossings. The cross vane may be constructed of wood (logs), stone (boulders), or a combination of both materials.

The regular cross vane is configured as two single-arm vanes on opposite banks connected across the center of the stream by a straight or semicircular crosspiece called the "sill" section. The cross vane provides grade control in two ways. First, the footer rocks extend below the expected scour depth to prevent upstream migration of knickpoints. A knickpoint is a point along the channel where there is a sharp change in the stream bed elevation, which creates a small waterfall that can erode upstream. Second, the vane creates an elevation change in the channel longitudinal profile, which allows lower bed slopes upstream and downstream of the vane, which in turn decreases the forces driving channel erosion.

Where applicable, the cross vane is a more ecologically beneficial alternative to traditional bank armor, such as riprap, or traditional grade control methods, such as check dams. The arms of the cross vane act as single-arm vanes, deflecting flows away from the bank and creating turbulence, which dissipates energy and thus lowers the applied shear stress near the bank. The flow deflection and resulting drop in applied shear stress improves the establishment of protective vegetation on bare or newly regraded banks.

Cross vanes can also increase flow diversity and fish passage in uniform channels. Water ponded upstream of the vane induces gravel deposition, creating a riffle. By forcing the flow over a drop and concentrating it in the center of the channel, cross vanes cause the formation of a scour pool downstream of the vane, further increasing flow diversity. In this way, a single cross vane creates a single riffle-pool structure while a series of cross vanes develops a riffle-pool sequence.

While "stable" streams naturally migrate over time, and the restoration of water quality and ecological integrity in degraded streams should be conducted in the context of the entire watershed, it is sometimes necessary to prevent lateral and/or vertical changes in stream channels, particularly in urban areas. Examples of such situations include the protection of roads or bridges from lateral channel migration or knickpoint migration and the maintenance of bank stability during vegetation establishment.

Figure 1. Cross vane on Upper Little Patuxent River, Maryland used to protect a sewer line which crosses the channel just upstream of the vane. (photo courtesy of Johnson, Mirmiran & Thompson, Inc.).

Application

The cross vane is effective for stream reaches which…

- are slightly-to-moderately meandering/sinuous;

- are actively incising;

- would naturally possess a riffle-pool sequence (i.e. Rosgen stream types A3-A4, B3-B4, C3-C4, F3-F4, and G3-G4 as described in Rosgen's 1996 text Applied River Morphology);

- have a moderate to high gradient;

- have coarse bed material (small boulders/cobbles to coarse sand), which is mobile enough for scour pool formation; and,

- have few or no regions of stagnant water or backwater.

In streams with steep bed slopes and/or knickpoints, cross vanes can be used to safely reduce the bed elevation and to prevent streambank erosion. Cross vanes can also be used to improve aquatic habitat.

Consider use of the cross vane carefully for stream reaches which…

- have no site constraints which require the stream to remain stationary and not naturally migrate across the floodplain;

- are deeply incised or have a low width to depth ratio, as the arm slope may exceed recommended values;

- are experiencing substantial change in their cross-sectional geometry, as additional structural stabilization measures may be required; or,

- have beds of very fine, mobile material (fine sands and/or silt), which increases the risk of structural failure by undercutting.

CAUTION: Cross vanes are costly and have a relatively high risk of structural failure due to their position within the stream itself, so they should be installed only to protect infrastructure or to provide grade control.

CAUTION: Do NOT install a cross vane in streams which…

- are composed of exposed bedrock;

- regularly experience heavy loads of large sediment (cobbles and larger) or other large debris (i.e. large logs) or,

- otherwise have little justification for preventing natural lateral channel migration.

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General Design Guidelines

The numerical guidance listed below represents rules-of-thumb that may not be strictly followed on a site-by-site basis and should not be substituted for actual design calculations and/or modeling. Please see the references section for a list of useful documents from which these numbers were obtained, most notably the Maryland Waterway Construction Guidelines (2000), Gordon et al. (2016), and the Sotiropoulis and Diplas (2014).

Design Flow

It is important to consider a range of low and high flows in stream restoration design. At low flows, structures should concentrate flows to maintain sufficient depth for fish passage and survival of aquatic organisms. Stability analysis at high flows should be conducted to ensure the vane remains in place for flows up to a given recurrance interval (return period).

The magnitude of the design flows will depend on project goals, as well as physical (site and valley), budget, regulatory, and other constraints.

One consideration in the selection of a high design flow is the desired structure design life (SDL). Inherently, the SDL indicates the likelihood that, in any given year, the vane might experience a flood event of greater magnitude than the design storm. The SDL is often determined by client needs or permitting requirements. In an urban watershed, in which structure failure may cause damage to nearby infrastructure or adjoining property, the acceptable level of risk is important to consider.

If the acceptable level of risk is provided in the form of a given recurrence interval, T, for the flow to be withstood by the structure, the SDL will be equivalent to that recurrence interval. For example, if local regulations require that all in-stream structures be designed to withstand a 50-yr flood event, then the SDL will be 50 years, and the design flow will be the 50-yr flood discharge. The probability of the design flood occurring in any given year is $P = 1/T * 100\%$. Thus, there is a 2% probability of the 50-year flood occurring in any given year.

The risk, R, of the structure experiencing a flow equivalent to the design flood during a given time period, m, is determined using the formula $R = 1-(1- 1/T)^{m}$, where m is the time period of interest in years. Thus, a single-arm vane designed for an SDL of 50 years will have a failure risk of 18% over a 10-year period.

Alternatively, the SDL can be determined by calculating the flow that will produce an applied shear stress or other hydraulic parameter that the vane must resist and then determining the recurrence interval of the associated flow.
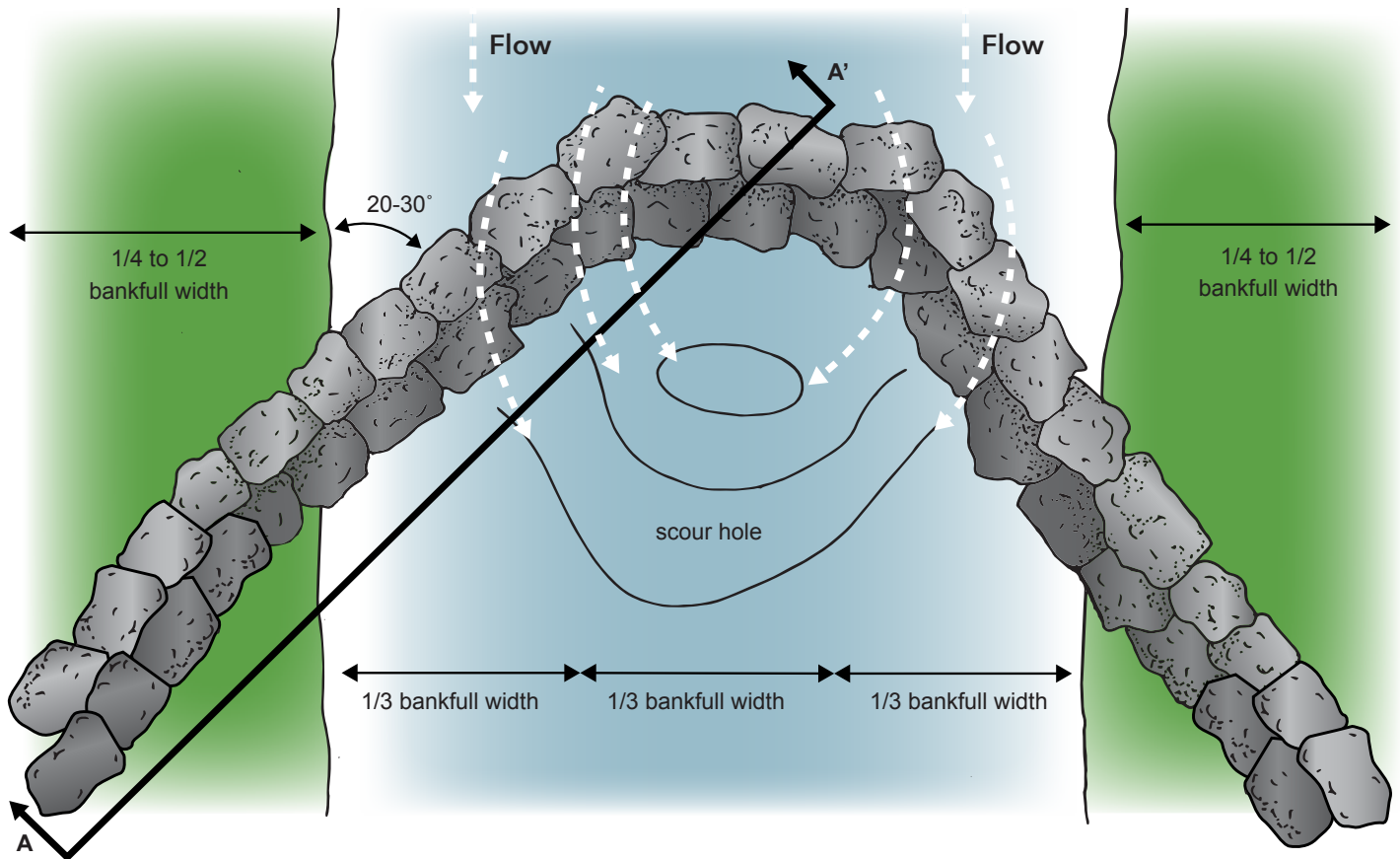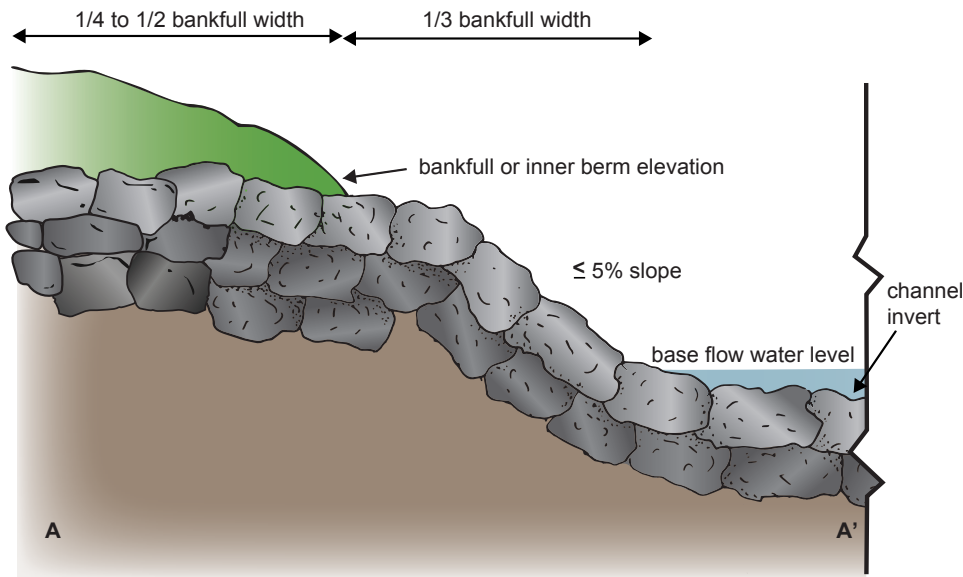

Figure 2. Cross vane plan view.

Figure 3. Cross vane section A-A'.

Material Sizing

Material used for a cross vane must remain structurally sound during the design flow. However, the materials used must also be small enough to create the cross vane geometry described below. Selected material sizes may need to be altered based on the geometry and size of the stream to produce a cross vane which has the correct configuration. As a result, the design life of the structure may be reduced. Alternatively, the rocks can be grouted to increase weir strength.

When sizing woody material for log arms, note the size of material locally available and the size of material naturally occurring as debris in the stream or a reference reach, and select materials that will replicate a natural condition for the stream. In general, use of single logs less than 8 in. (20 cm) in diameter is not recommended. Additionally, logs should be long enough to key into the bank 1/4 to 1/2 bankfull width. Smaller logs may be used in a bundle if they are bolted together.

To size boulders for the cross vane, the minimum size rock which will remain in place during the design flow must be determined. The flow exerts a shear stress on any material in the channel; this is called the applied shear stress. The critical shear stress of a particle (boulder) is the shear stress at which it will likely be displaced. Because different channel cross section geometries can produce the same average flow velocity, it is important to assess the stability of the materials using shear stress, rather than an allowable velocity. Technical Supplement 14C Stone Sizing Criteria of the NRCS Stream Restoration Design Handbook (NRCS, 2007a) describes these calculations in greater detail. Designers should recognize that techniques used to size riprap may underestimate the size stone needed for in-stream structures because the vane rocks are more exposed to the flow than riprap. Once a material size is calculated, a factor of safety of 1.1-1.5 is commonly used. Rocks used in cross vanes are typically 2-4 ft. (60-120 cm) in diameter. Designers should also consider using stones which are large enough to prevent movement by vandals.

Material Selection

The choice between use of logs or rocks for the cross vane should be made considering both the goals and requirements of a particular project, the materials which occur naturally in the stream (or a reference reach), and materials available on site.

Woody material (logs) is generally less expensive than rocks, and may be more readily available. Use of logs should be seriously considered in streams that naturally have a high occurrence of large in-stream woody debris, rather than large in-stream boulders. However, logs are generally not recommended for use in grade control structures unless the stream has a high occurrence of large in-stream woody debris. Since wood is a biological material, natural decay will significantly limit the life expectancy of a log-arm cross vane. So, if a longer SDL is required by the project, which is likely for a grade control structure, a log cross vane may not be a viable option. Wood that is continuously submerged will have a greater life than wood exposed to wetting and drying.

Boulders are more expensive than logs, but are more durable, as their natural decay

CAUTION: Use of log vanes in streams with highly variable flows (such as those in urban settings) or for projects involving infrastructure protection is not recommended due to the lower durability of log arms. In addition, log arms are more easily undercut than rock vanes, so use caution when designing log arms for a stream with fine, mobile bed material.

occurs over a much longer period of time. Rock vanes may also be easier to construct, as the key is made of multiple individual boulders, rather than the same single log as the vane. Rock vanes are particularly recommended for projects which require a long SDL or involve the protection of infrastructure, and for streams in which large boulders and rocks are normally found.

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Sill rocks should be large enough to remain secure in the streambed. These rocks will bear the brunt of the hydraulic force. Footer rocks used below the sill should belarger than the sill rocks themselves.

Choose rocks which have flat, rather than round, surfaces to allow the vane rocks to sit securely on the footer rocks and to line up with adjacent rocks. When placing rocks, remember that the rocks nearer the sill will experience the strongest hydraulic forces. In general, larger rocks will produce more turbulence, leading to a deeper scour pool. Also be sure to consider rock mineral composition, as rocks such as sandstone can have lower density and some minerals can experience high rates of weathering or chemical leaching. Use native stone when possible.

Footer Depth

As water crosses over the vane arms, it will drop and impinge on the channel bed, causing a scour hole (plunge pool) to form. While this scour hole increases bedform and flow diversity, if it becomes deeper than the footer materials, the structure can be undermined. Therefore, it is critical to estimate the scour depth downstream of the structure over a range of flows to ensure the footers or piles for log vanes extend below the maximum predicted scour depth. The expected scour depth can be determined using the methods described in Technical Supplement 14B ("Scour Calculations") of the NRCS Stream Restoration Design Handbook (NRCS, 2007b) and in Gordon et al. (2016). These methods frequently require knowledge of both the headwater and tailwater depths at multiple stream discharges; therefore, the design reach should be modeled using softwater such as HEC-RAS, as described in Gordon et al. (2016).

CAUTION: If the channel substrate has a high sand content, use the Wilcock-Kenworthy modification of the Shields number, as described in Wilcock et al. (2008) to determine the critical shear stress.

In designing structure footers, it is important to realize that the greatest scour will occur where there is the greatest drop height. Because the vane arms are sloped up from the sill, the greatest drop will occur along the vane arms, closest to the bank. However, this is also the area with the lowest footer depth (assuming the footers are parallel to the vane arms. To provide greater support along the arms, the footer depth can be extended or larger rocks can be used under the vane arms.

If the cross vane is being used to prevent the migration of a downstream knickpoint, it is important to estimate the maximum bed degradation that could occur at the structure due to the knickpoint. Footer depth should then be based on the greater of either the scour pool depth or the bed degradation due to the knickpoint. Once the maximum bed degradation is estimated, the footer depth or piling should extend 1.5-3.0 times this expected depth, or until a resistant layer, such as bedrock, is reached.

Placement within Stream Cross-Section

Install the vane arms at a 20° to 30° horizontal angle from the bank, such that the vane points upstream. Measure the angle between the vane and the upstream bank (see plan view diagram, Figure 2). Including the sill, the whole cross vane should form a "U" shape with the apex pointed upstream. A larger angle between the arms and the banks can protect greater lengths of bank against erosion, but also results in more intense bed scour and greater risk of failure. In highly sinuous channels, a smaller horizontal angle reduces the risk of erosion just upstream of where the vane is keyed into the bank. However, because water will flow perpendicular to the vane arm, in smaller streams, smaller horizontal angles can direct flows into the opposite bank, causing bank erosion downstream of the structure.

The vane should be keyed into the bank so that the vertical slopes of the arms do not exceed 5% for rock arms and 4% for log arms. As the angle of the vane increases, so does the distance between the top of the vane arm and the bed, increasing the water drop height and the amount of scour

CAUTION: Placing the vane arms at a larger angle to the bank (30 degrees) in a stream with a fine gravel or sand (highly erodible) bed may cause undesirable bed erosion as the scour depth immediately downstream of the vane increases with increasing horzinontal vane angle.

that will occur. Although prior design guidance (Rosgen, 1996) indicated the vane should be keyed in at bankfull height, this will not be appropriate for every stream, and log vanes in particular should be keyed in lower than bankfull height, as they generally require a lower vertical slope (B.A. Doll, personal communication, April 11, 2016).

The sill rocks or logs should be submerged at all times. The rocks or logs at the tips of the arms (not just the footer materials) should be buried in the stream bed at approximately thalweg elevation to allow sediment transport and fish passage.

Each vane arm typically does not extend over more than 1/3 of the bankfull width. The sill covers the middle 1/3 of bankfull width in the stream center. While the vane arms are traditionally symmetric (i.e. same horizontal angle and length), asymmetric vane arms may be used to provide additional protection along one bank or to redirect flows. In smaller streams, the sill may not be included, forming a "V" shape; however, this shape is more prone to failure as the vane arms may redirect high-energy flow at the opposing arm, increasing bed scour and undermining the structure.

An alternative form of the cross vane is the A-type cross vane, which features an extra step linking the two arms 1/3 to 1/2 of the vane length away from the sill (Figure 4). This step acts as an additional vortex, creating a structure in which two scour

CAUTION: The greater the vertical slope of the vane, the shorter the length of bank the vane will protect from erosion.

pools are formed (one between the two vortices and the other downstream of the vane), reducing both the depth of scour and the elevation change at each sill.

Placement within Stream Planform

Not only will a cross vane prevent stream bed incision, it will also prevent natural migration of the channel across the floodplain. If natural channel migration cannot be allowed, such as to protect infrastructure, a similarly confined reference reach can be used to inform structure spacing along the channel. In undisturbed meandering streams, pools commonly occur every 5 to 7 bankfull widths apart along the stream channel. If infrastructure protection or grade control is not a project goal and the stream can be allowed to migrate naturally, cross vanes should not used.

Because bed material will deposit upstream of a cross vane and a scour pool will form downstream, cross vanes should be placed in a run on meandering channels. Cross vanes placed in a meander bend tend to fail due to structure flanking as the meander bend migrates.

In channelized streams where there is not sufficient space to create meanders, due to the presence of buildings or other infrastructure in the floodplain, a series of cross vanes can be used to create a step-pool channel, which reduces boundary shear stress and improves aquatic habitat, as compared to hardening the channel with riprap or concrete. Cross vanes are more successful when spaced closely together; however, when used for grade control, they should be placed no closer than the net drop height divided by the channel slope. Additional detail on siting grade control structures is provided by Biedenharn and Hubbard. Also, the cross vanes should not be so closely spaced that downstream structures are affected by the scour pool of the upstream structure. A study by Gordon et al., 2016 showed pool length can extend from the sill to a distance equal to two times the vane arm length. Additionally, each vane should not increase the water surface elevation above the height of the upstream vane. Water depth over the vane can be estimated using stage-discharge relationships developed by Gordon et al. (2016).

Note that no individual cross vane should produce a bed elevation change of more than 2 ft. (0.6 m), to ensure the developed scour pool does not undermine the vane footers, as scour depth increases with increasing step height. Due to the lower durability of log arms and greater susceptibility to undermining, no log cross vane should create an elevation change in the bed of more than 0.5 ft. (0.15 m). The bed elevation change should also be limited to 0.5 ft. (0.15 m) if fish passage is a design goal.

Cross vanes designed to protect infrastructure, such as bridges, should be installed such that the sill is 1.5 to 2.0 times the bankfull width upstream of the bridge abutment. This location reduces the likelihood that the scour pool will form adjacent to the bridge foundation while still diverting flows towards the center of the channel For A-type cross vanes, extend this distance to 2.5 to 3.0 bankfull channel widths. If applicable, the hydraulic behavior of the existing bridge should also be evaluated as part of the design.

Construction

The most common failure modes for cross vanes are undermining of the structure, structure flanking, and loss of vane rocks.

Footer rocks/logs and wooden pilings are used to prevent scour from undermining the vane. One or more tiers of footer rocks may be used, depending on the susceptibility of the vane to structural failure by undercutting. During construction, slightly offset vane rocks into the flow (in the upstream direction), such that a bit of the footer rock is exposed on the downstream vane face. This offset prevents the creation of a scour hole directly on the downstream face of the vane which would undermine the structure, perhaps even causing vane rocks to collapse into the scour hole.

To prevent bank erosion where the vane is attached to the bank, it is important to "key in" the vane arms. Anchor the bank end of each arm into the bank a distance 1/4 to 1/2 bankfull width. Large boulders may be placed on the downstream side of the vane arms to increase structural stability. This increased support is provided along the downstream face where the vane is anchored into the bank.

Even though rocks may be sized correctly for the design flow, individual rocks may be dislodged due to turbulence around exposed rocks or flow between rocks. All rocks used in a cross vane should fit together snugly (Figure 4). Offset vane rocks from footer rocks such that each vane rock is centered on the intersection

Figure 4. A-vane, Paint Branch, College Park, Maryland.

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of two footer rocks, resting on half of each. To prevent sediment from eroding through gaps in the footer rocks, hand-chink any gaps that exist between rocks with gravel with a wide range of particle sizes and wrap the footer in geotextile fabric.

Post-Construction Monitoring

The function of most structures can be assessed using repeated visual observations and photographs. Some additional monitoring activities to evaluate vane function include the following:

- measure scour pool depth to ensure a pool is forming and the pool depth does not exceed the depth of pilings or footer rock layers;

- regularly examine the adjacent streambanks for erosion or a lack of vegetation establishment;

- examine the vane for rock displacement after storm events of a similar magnitude as the design storm, where displacement is defined as complete removal of the rock from its place, rather than minor shifting;

- regularly examine the vane for aggradation or bed degradation upstream of the structure; and

- ensure that the vane is not creating tailwater depths greater than upstream structure elevations (i.e. upstream structures are flooded at baseflow).

If visual assessment of the structure indicates undermining, lateral erosion, or aggradation of the structure, additional assessments, such as cross section and longitudinal surveys, can be conducted to determine what corrective action may be needed.

Consider requesting help from local conservation or volunteer-based organizations for monitoring work that can be performed by laypeople, if resources for monitoring are unavailable or limited.

Figure 5. Vane rocks should fit snugly together and be chinked with smaller rock with a wide range of sizes. (Design by Wetland Studies and Solutions, Inc.)

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